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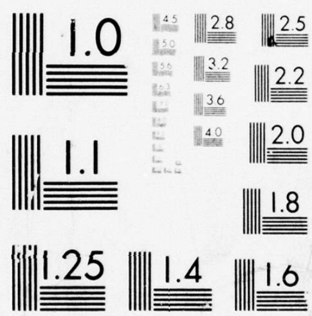

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DEVELOPMENT OF A CATALYTIC COMBUSTOR FUEL / AIR CARBURETION SYSTEM

GENERAL APPLIED SCIENCE LABORATORIES, INC.
MERRICK AND STEWART AVENUES
WESTBURY, NEW YORK 11590

MARCH 1977

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AIR FORCE AERO-PROPULSION LABORATORY
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This report has been reviewed by the Information Office, (ASD/OIP) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

Thomas J. Rosfjord

THOMAS J. ROSFJORD, Capt, USAF
Project Engineer

FOR THE COMMANDER

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Candidate fuel/air carburetion systems were screened to determine their ability to produce a uniform mixture of Jet A fuel and air. Pressure, air blast and air-assist atomization techniques were examined. The air-assist fuel injection scheme was selected as most appropriate and was modified by the use of a variable angle swirl generator to produce acceptably flat fuel and velocity profiles at the system exit. The device was tested over a range of air velocity, inlet pressure, inlet temperature and fuel/air ratio. Profiles of velocity, fuel concentration and degree of vaporization were measured → over

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at the exit plane and at an intermediate station 75% of the distance between the injector and the exit. Velocity profiles were found to have a standard deviation of only 10.5% from the ideal case, while the average deviation of the fuel concentration profile was 8.3% from ideal. Measurements indicated that the complete vaporization was achieved prior to the system outlet plane. Two units of the tested system were fabricated and delivered to the Air Force Aero Propulsion Laboratory.

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INTRODUCTION

A catalytic reactor may be divided into three primary components: the catalytic material, the catalyst support structure or substrate and the fuel/air carburetion system. Early research on catalytic reactors has concentrated, and continues to concentrate, on the catalyst and substrate. The fuel/air carburetion system, an essential element of the catalytic reactor concept, has received little attention to date. However, the functioning of a practical carburetion system is an important element of overall catalytic reactor operation and a full and realistic assessment of the potential of catalytic reactors cannot be completed without a thorough understanding of the operation of the carburetion element.

The most commonly employed form of catalyst bed is the honeycomb which is placed within a combustor duct and functions as a bundle of tubular reactors. The temperature within each reactor tube increases monotonically as energy is released by the oxidation reactions occurring in the gas flowing through it. Aside form a small degree of conductive heat transfer, the final temperature within each reactor tube is a function of the fuel/air ratio of the mixture which enters and the degree of fuel vaporization. Locally high fuel concentrations can produce unacceptably high reactor tube temperatures, either directly damaging the catalyst or substrate or subjecting the structure to abnormally high thermally-induced stresses. Locally low fuel concentration produces lower combustion efficiency. A similar argument can be made for the velocity, since the efficiency of a catalytic reactor tube is related to the mass flux which it must process.

Clearly then, the fuel/air carburetion device employed in a catalytic reactor is required to produce a stream of acceptable uniformity with respect to both equivalence ratio and velocity. In addition, since reactions occur within the gas phase, it is necessary that liquid fuels be allowed to vaporize prior to entering the reactor. The effect of residual liquid fuel entering the reactor is not yet known. However, incomplete vaporization certainly reduces the effectiveness of the upstream portion of the reactor by reducing the gas phase equivalence ratio and may possibly be a contributing factor to long term deacti-

vation of the catalytic surface.

It is evident that the development of an effective and reliable carburetion system is an integral part of the development of the catalytic reactor. In addition, since any fixed physical carburetor system design will, of necessity, display some sensitivity to operating conditions, it is necessary that any final design be carefully tested over the spectrum of anticipated operating conditions to assure that its sensitivity level is within acceptable limits. It is, therefore, necessary to define the limits of acceptable operation in terms of pressure drop, degree of evaporation and degree of uniformity of velocity and fuel distribution. An acceptable design will meet these limits at all operating conditions. Verification testing will not only document this ability, but will also indicate the degree of nonuniformity to which the catalytic reactor is subject under varying entrance conditions, information which will greatly aid in the evaluation of the performance of the reactor element itself.

This report presents the results of a development program whose goal was the evolution of an effective fuel/air carburetion system for use with a catalytic gas turbine combustor. The basic operating point for the carburetion system is defined by a combustor reference velocity* of 100 ft/sec, a total pressure of 100 psia, an entrance temperature of 850°F and a fuel/air ratio of 0.023 (equivalence ratio 0.35) using Jet A fuel.

Each of the basic operating parameters (pressure, temperature, velocity, fuel/air ratio) has been varied to produce a matrix of operating points spanning the following ranges:

Pressure:	100, 150, 250 psi
Temperature:	700, 850, 1000°F
Velocity:	75, 100, 125 ft/sec
Fuel/Air Ratio:	0.018, 0.023, 0.028

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*Reference velocity is defined as mass flow divided by combustor entrance density and cross sectional area.

The resulting matrix of operating conditions is presented in Table I. Condition I of Table I does not represent an operating point per se: rather, it represents a condition at which the ability of the design to avoid autoignition and/or flashback can be assessed. The ability to preclude the occurence of these phenomena at one half the basic operating velocity represents a conservative feature of the design and provides a reasonable margin of safety to handle inadvertent fluctuations which may occur during operation.

TABLE I

SUMMARY OF OPERATING CONDITIONS

Condition	Fuel/Air (Mass/Mass)	Temperature (^{o}F)	Pressure (psia)	Velocity (ft/sec)
1	0.023	850	250	50
2	0.023	850	100	100
3	0.018	850	100	100
4	0.028	850	100	100
5	0.023	700	100	100
6	0.023	1000	100	100
7	0.023	850	150	100
8	0.023	850	250	100
9	0.023	850	100	75
10	0.023	850	100	125

The problem was approached by selecting three candidate carburetion system designs, each of which had shown promise in similar, though not identical, applications. The candidate systems selected represented a spectrum of fuel injection techniques employing pressure, air-assist and air-blast atomization schemes. The performance of each of these candidate designs was evaluated at four operating conditions (conditions 1, 2, 5 and 10). Three criteria were used for performance evaluation. First, each candidate must demonstrate the ability to operate at condition I without producing autoignition in the mixer

or flashback from the combustor. Second, the maximum normalized RMS deviation of a seven point profile at the combustor entrance station must approach a design goal of no more than 10% with regard to degree of evaporation and 5% with regard to fuel and velocity uniformity. Third, the maximum deviation of any measured point from the ideal must approach a design goal of no more than 20% with regard to degree to evaporation and 10% with regard to fuel and velocity uniformity. Based on the results of these screening tests, one system was selected for modification for performance improvement. Finally, the performance of this modified design was fully documented at all operation conditions. Two copies of the final design were fabricated and delivered to AFAPL for use in an in-house program.

Section II of this report contains a discussion of the general design considerations which were applied to the fuel/air carburetion system and a description of the three candidate systems screened in this program. Section III presents the results of the initial screening tests and Section IV details the performance changes produced by various design modification. Finally, the complete performance capabilities of the final design configurations are summarized in Section V.

**The normalized RMS deviation of n measurements of the quantity ψ from an ideal condition $(\ )_i$ is defined as

$$\alpha = \left[\frac{1}{n} \sum_{k=1}^{n} \left(\frac{\psi - \psi_i}{\psi_i} \right)_k^2 \right]^{\frac{1}{2}}$$

SECTION II

DISCUSSION OF DESIGN APPROACHES

The carburetion process consists of three basic steps: distribution of the liquid fuel, evaporation of the liquid and gas phase mixing. Due to constraints related to avoiding autoignition, the total length available to accomplish these three steps is relatively short, amounting to no more than a few mixer tube diameters. Since the degree of gas phase mixing which can be anticipated within so short a distance is quite modest, the initial step of distributing the liquid fuel across the incoming airstream is highly critical as the degree of uniformity achieved in liquid distribution is a strong factor in determining the degree of uniformity achieved by the mixer exit plane. Liquid evaporation is another critical element of the design scheme. Since the state of the incoming airstream is given, the bulk fuel evaporation rate can only be affected by varying the fuel surface area. These constraints lead to the selection of an atomization system for fuel injection as opposed to a surface evaporation technique.

Several fuel atomization techniques are available and suitable for consideration in the present design. Each offers certain advantages; each imposes certain constraints. Pressure atomization is a simple technique which produces relatively small fuel droplets and has the advantage of high initial droplet velocity relative to the airstream. This high relative velocity offers the potential of producing a good initial dispersion of droplets throughout the stream; an important advantage. Good pressure atomization does require very small injector orifice area, a constraint which could lead to clogging. More important, however, is the fact that varying the fuel flow rate through a pressure atomizer is accomplished by varying the injector pressure drop and hence the droplet diameter and injection velocity. As a result, pressure atomization will produce an initial fuel dispersion which will vary with the fuel injection rate.

Air blast atomization is another relatively simple technique with important advantages in the present application. Although specific designs vary widely, the air blast atomization principle involves forming a thin film of fuel over a

solid surface and allowing this film to be shattered by the shearing action of the external airflow. The technique offers the important advantages of a large injection orifice area and an initial fuel distribution which is independent of fuel flow rate. It suffers from the disadvantage of relatively large expanses of injection surface within the airstream and a droplet size which, at the air velocities available here, is larger than that which can be achieved using pressure atomization.

Finally, air-assist atomization is also well suited to the present problem. In this case, an auxiliary supply of pressurized air is used to provide the energy to atomize the liquid stream. Air-assist atomization offers the advantages of large injection orifice area, small droplet size and a droplet distribution which is relatively insensitive to fuel flow rate. Although these atomizers suffer from the drawback of being relatively bulky, they offer the important advantage of providing an additional design parameter, viz. auxiliary airflow rate, which can be varied to offset the effects of other operating variables over which there is no control.

The three candidate systems selected for screening in this program differed only in the fuel injection technique which they employ. Pressure, air blast and air-assist designs were each evaluated in terms of their ability to produce a good initial dispersion of droplets with diameters small enough to produce essentially complete evaporation within a relatively short downstream distance. Further design considerations, involving an essentially gas phase mixture, apply equally to all design concepts.

Since the carburetion system produces a combustible mixture of fuel and air, an important design constraint is the avoidance of combustion upstream of the system exit. Upstream combustion can result from either of two phenomena: autoignition or flashback. In principle, autoignition can be avoided if the residence time within the carburetion unit is less than the ignition delay time for the mixture. Achieving this result in a practical design requires not only the proper matching of flow velocity with carburetor length to limit bulk residence time, but carefully avoiding regions of local separation where recirculation produces residence times from three to four times

longer than those characteristic of the bulk flow. This can be accomplished by carefully contouring the carburetor walls, avoiding protuberances such as mixing plates and vortex generators downstream of the fuel injection station and placing all struts, in-stream fuel injectors, etc., in regions of favorable pressure gradient where wake closure is accelerated.

Ignition delay data for mixtures of Jet A fuel with air is not currently available at the pressure levels of interest here. However, Reference (1) does present data for mixtures of JP-4 and air at pressures up to 240 psia and the fundamental similarity between JP-4 and Jet A justifies the use of this data as a design guide. The most severe condition, from the autoignition standpoint, is that denoted as condition 1 ($T = 850^{o}F$, $p = 250$ psia) where an induction time on the order of 18 msec is to be anticipated. At a constant mixer velocity of 50 ft/sec, this condition would produce ignition in a distance of eleven inches.

The diameter of the catalytic reactor section was set at three inches. Using a mixing tube length of eleven inches would result in a length-to-diameter ratio of less than four, an unsatisfactory situation from a mixing point of view. Improving this situation without increasing residence time requires that the mixer diameter be reduced. However, achieving a uniform mass flux loading at the reactor entrance station also requires matching diameters at that point. Therefore, we are led to the use of a convergent-divergent mixer tube geometry in order to improve gas phase mixing without sacrificing the ability to avoid autoignition.

The second problem, flashback, is defined as the upstream propagation of a flame from a stabilized source into a premixed flow. Flashback is essentially a balance between bulk flow velocity and turbulent flame propagation. If the two are nearly the same the flame location can be unstable. Although definitive data is lacking, operation of premixing, prevaporizing combustors has generally shown that upstream propagation of the flame occurs at mixer velocities on the order of 50 ft/sec. This does not imply that operation at mixer velocities barely above this level would be adequate to avoid flashback. The reason for this lies in the relatively low Mach numbers with which we are

dealing. At the high temperature condition, a velocity of 75 ft/sec corresponds to a Mach number of only 0.04. At this Mach number, an instantaneous pressure increase as small as 0.1% can cause local flow reversal and will produce flashback. In fact, operational experience at GASL indicates that although low bulk velocities are capable of reasonable operation at steady state, they often produce flashback during flow transients when pressure waves are most likely to develop in the system.

As a general design principle, flashback avoidance requires that two conditions be met. First, the bulk velocity at the combustor entrance station must correspond to a Mach number high enough to preclude flow reversal by pressure disturbances of a magnitude which might reasonably be expected in the system. Second, the design must provide no flame stabilization regions within the carburetor so that any flame propagated upstream by a pressure disturbance of unusual magnitude will blow back downstream as soon as the pressure disturbance decays.

The three candidate designs screened in this program employed the same basic mixer tube geometry, illustrated in Figure (1). The mixer tube consists of a 3-inch diameter entrance section, a rapid constriction to a 1.75-inch diameter throat (area reduction of 3:1) and a 5% half angle diffuser. The overall length of the device, from fuel injection station to exit plane, is 12-inches, and results in a residence time of 15 msec at the lowest flow velocity (condition 1, 50 ft/sec). Avoiding flashback requires that the local velocity at the entrance to the combustion zone be increased substantially above the mixer tube level. This high combustor entrance velocity is produced with the use of a porous plate flameholder at the mixer tube exit. The plate is provided with an evenly spaced array of 1/4-inch diameter holes to produce an open area equal to 20% of that available in the mixer tube. Together with an estimated discharge coefficient of 0.7 for the sharp edged holes, the geometric constriction produced by the flameholder increases the local velocity at the combustor entrance station to just over 350 ft/sec with a corresponding Mach number of 0.2. At this condition, combustor static pressure perturbations would have to be in excess of 3% of the stagnation pressure in order to cause local flow reversal.

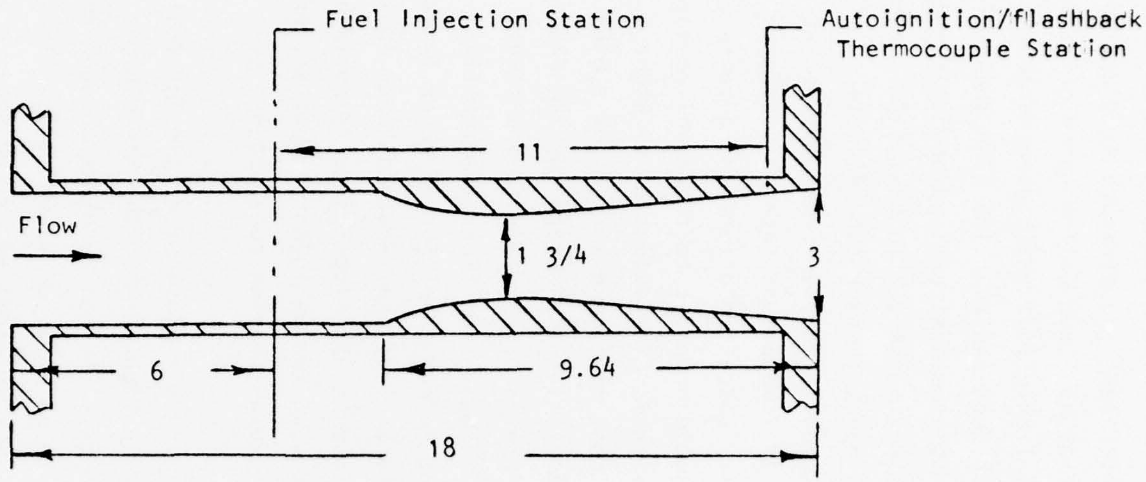


Figure 1. Mixer Tube Geometry

The pressure atomization design, designated Concept A, is illustrated in Figure (2). Concept A is similar to a design employed successfully in References (2), and is characterized by a pressure atomization fuel injection system consisting of a set of eight flush wall mounted orifices. Each orifice produces a straight column of liquid fuel which penetrates the airstream to approximately 80% of the mixer duct radius. The high shear of the air against the sides of the liquid columns atomizes them and produces eight sheets of droplets. The characteristic mixing length in design A is the lateral spacing between liquid sprays rather than the mixer tube diameter. The fuel injection orifices used in design A were individually removable and externally manifolded to eliminate the possibility of inadvertent internal leakage. A typical injector is shown in Figure (3). Concept A offers the advantages of extremely clean flow and low total pressure drop due to the complete absence of wake-producing devices in the airstream. The selection of eight fuel injection orifices stems from the fact that orifice diameters of 0.018-inched have been found to represent a practical limit with regard to clog-free operation. Since the penetration distance is related principally to the liquid jet velocity (c.f., References 3 and 4), fixing the orifice diameter fixes the mass flow of a single injector. Hence, the selection of jet diameter fixes the number of jets which must be employed to achieve the required total fuel flow rate. In this case, although a larger number of injection ports would have been desirable (Reference 2, for example, employs twelve injection ports), practical orifice size constraints limited the present design to eight ports.

Design concept B employs the air blast principle for fuel atomization and dispersion and is illustrated in Figure (4). The key element of concept B is the fuel shear blade. Fuel enters the hollow blade through the base and is distributed over the surface by an array of bleed holes. The fuel forms a film over the blade surface which is then atomized by the shear of the external airstream. Design B utilizes eight fuel shear blades to produce an initial dispersion pattern very similar to that obtained with design A. In this case, the radial distribution of fuel can be controlled, independent of fuel flow rate, by a suitable specification of the bleed hole pattern.

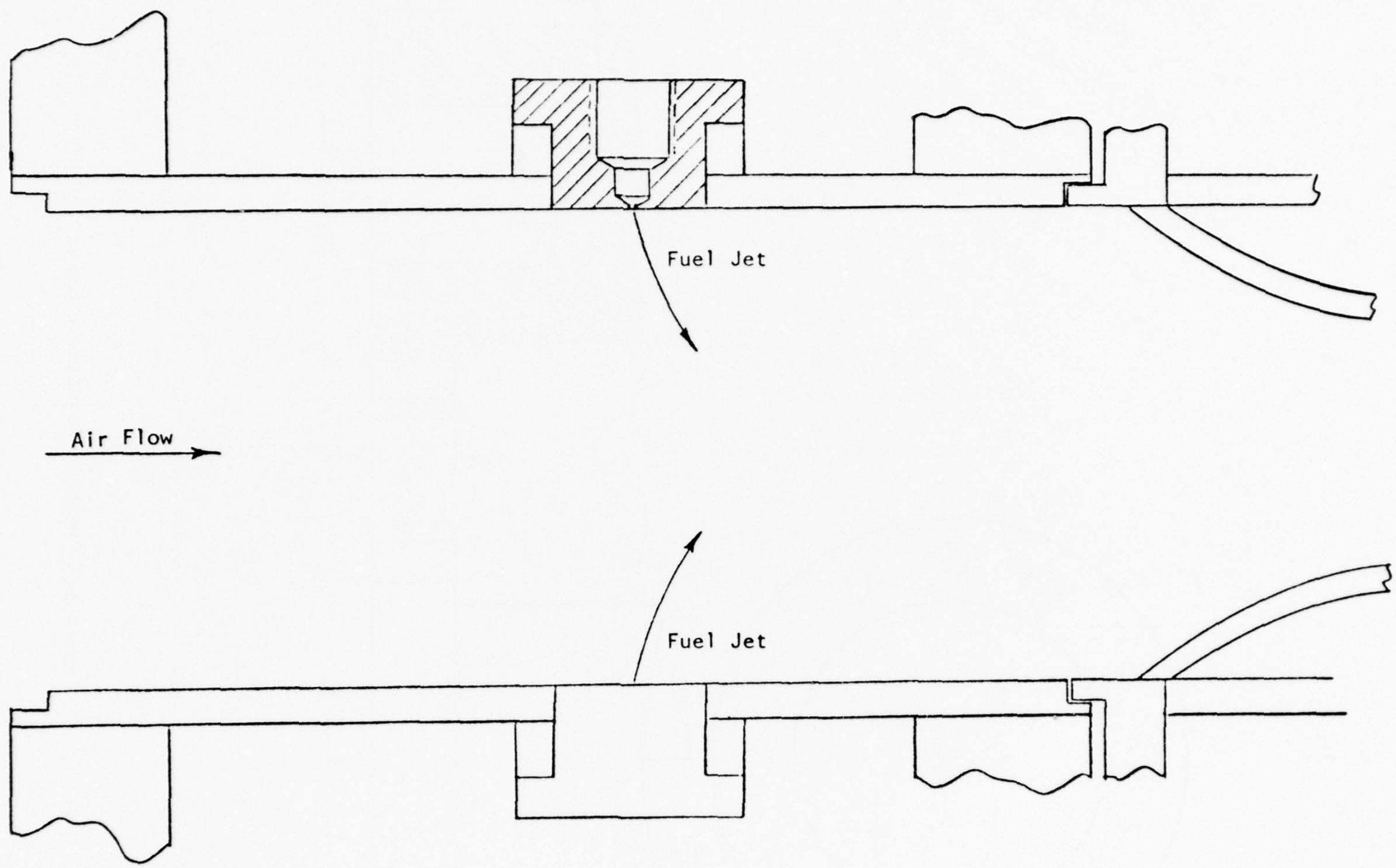


Figure 2. Design Concept A - Pressure Atomization

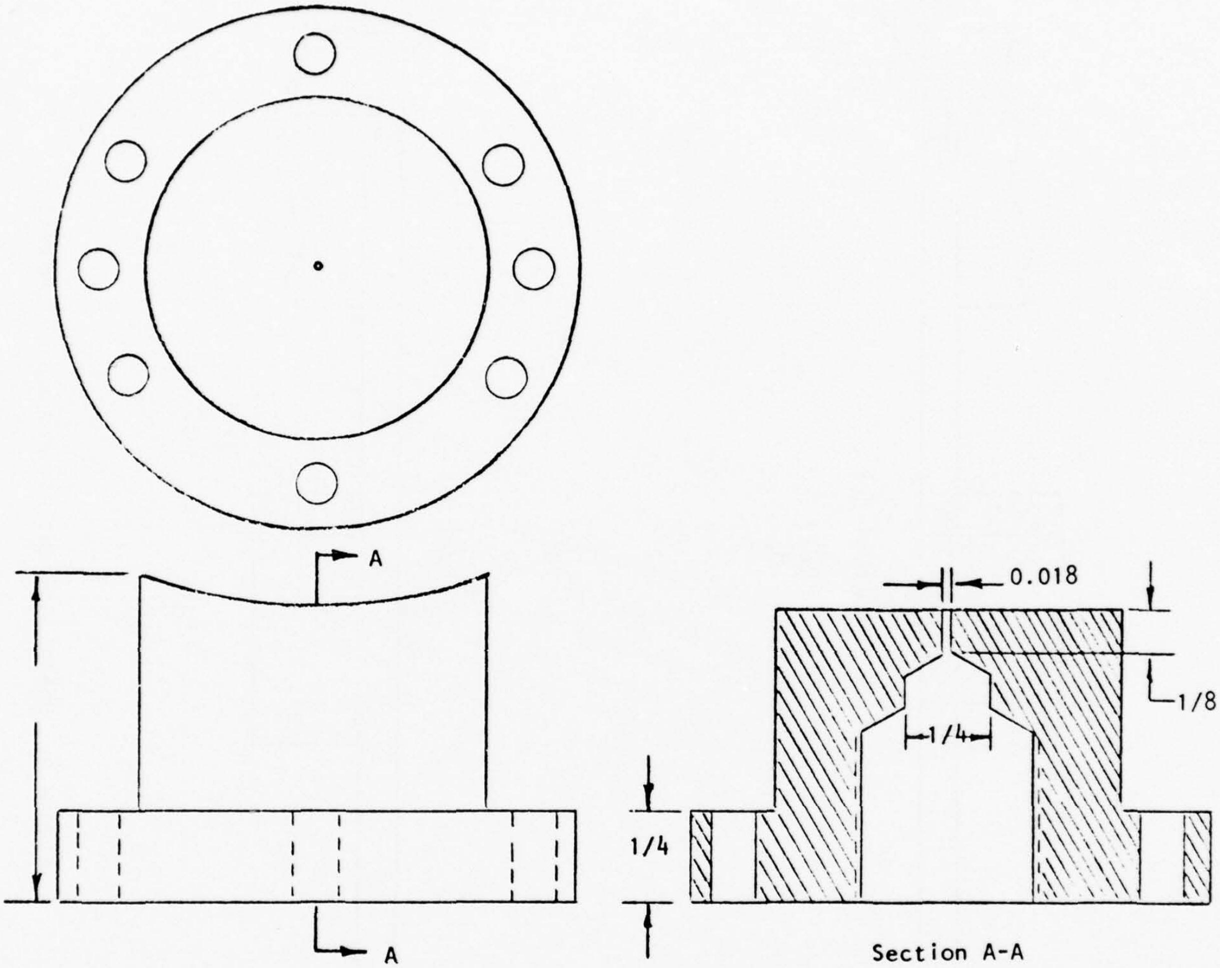


Figure 3. Pressure Injector Element

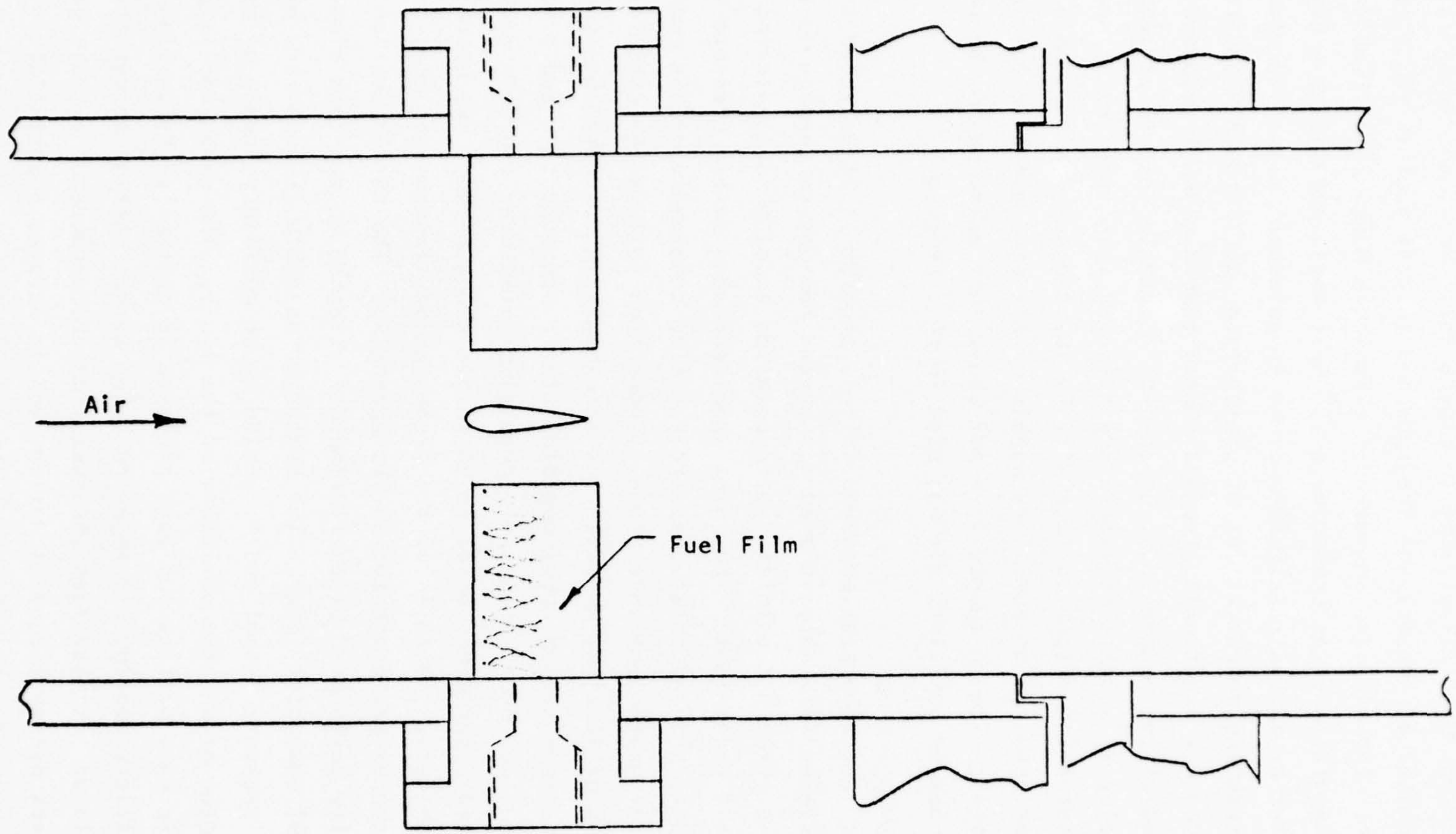


Figure 4. Design Concept B - Air Blast Atomization

Design concept C is illustrated in Figure (5). Here, an air-assist atomizer is mounted at the axis of the tube and injects fuel in the streamwise direction. The atomizer employed is a Sonicore Model 250 J-1 which is rated by the manufacturer as producing a 45^{o} half angle spray with a mean droplet diameter of approximately 60 microns in quiescent air. The atomizer operates by expanding a central jet of pressurized air through a central orifice to produce a supersonic stream directed toward a small resonator cap suspended ahead of the nozzle body, generating a locally intense ultrasonic field. Low velocity streams of liquid are directed into this region where they are shattered and dispersed laterally by the expanding air. The air-assist atomizer requires an auxiliary supply of air at a pressure ranging from approximately five to twenty five psi above that existing in the carburetion unit. Unheated auxiliary air was used in this program.

The basic test apparatus employed in this program is illustrated schematically in Figure (6). Dry, heated air enters the device through the bell mouth and flows through the inlet instrumentation spool before entering the carburetion unit under test. The inlet spool contains static pressure taps and total temperature and total pressure rakes to completely define conditions at the carburetor entrance plane. There then follows the carburetion unit and combustor section, separated by an exhaust instrumentation spool. The exhaust instrumentation spool contains static pressure taps and a movable probe which provides measurements of local pitot pressure, fuel/air ratio and liquid/gas phase discrimination at seven points along each of two mutually perpendicular diameters. (Details of the probe design, instrumentation, and data analysis procedures are presented in the appendix.) The burner section employs the 20% porosity perforated plate flameholder attached to a 4-inch diameter stainless steel combustor liner. The combustor assembly is supported within a heavy outer pressure vessel and is cooled by an auxiliary supply of cold air which is injected around the periphery of the liner. The combustor is provided with a sonic exit orifice and back pressure is controlled by varying the amount of auxiliary cooling air injected. The burner section serves three important functions: it scavanges the fuel from the carburetor exhaust gas, it serves as a back pressure control device, and it acts as a potential source of ignition for evaluating the flashback characteristics of the various designs.

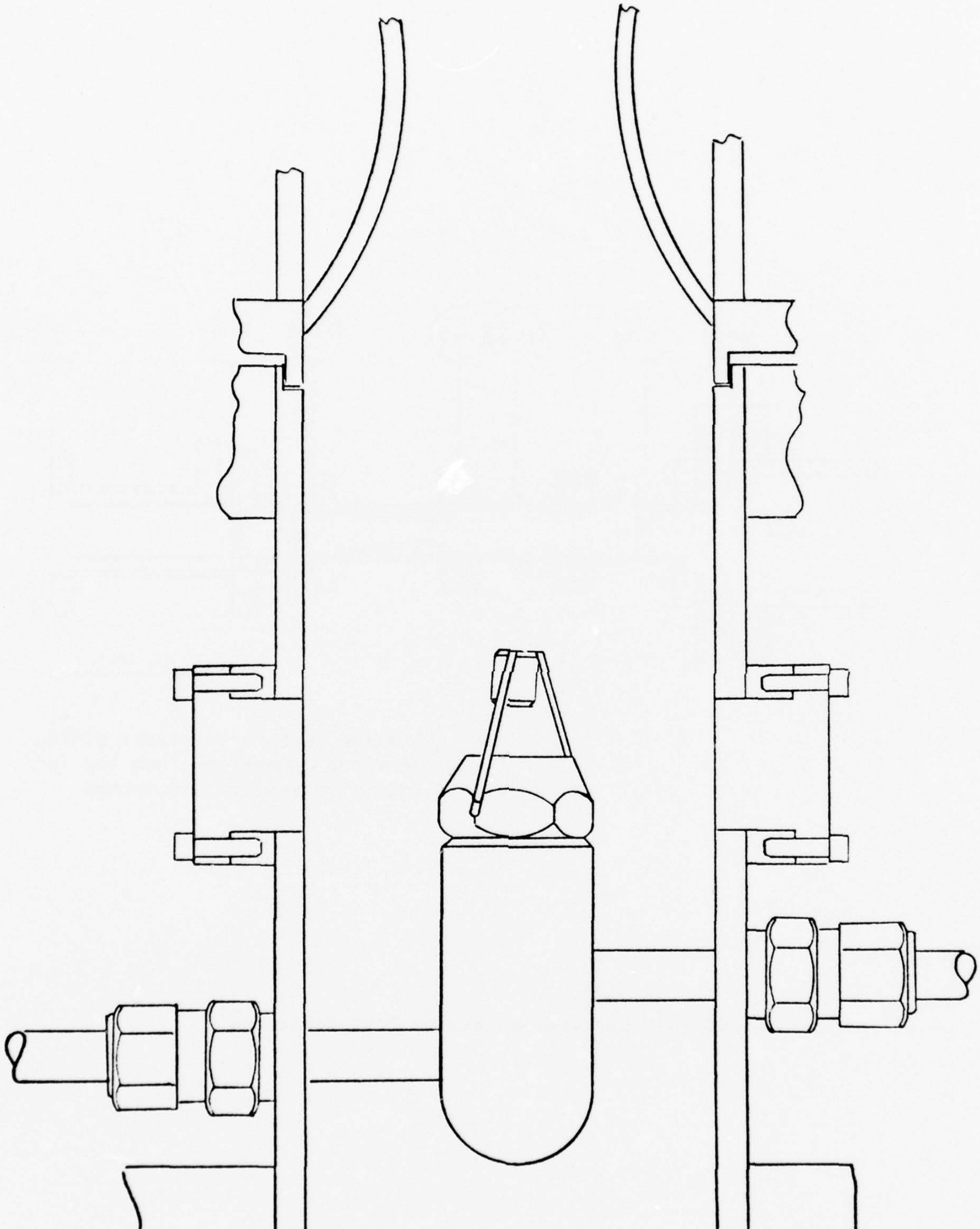
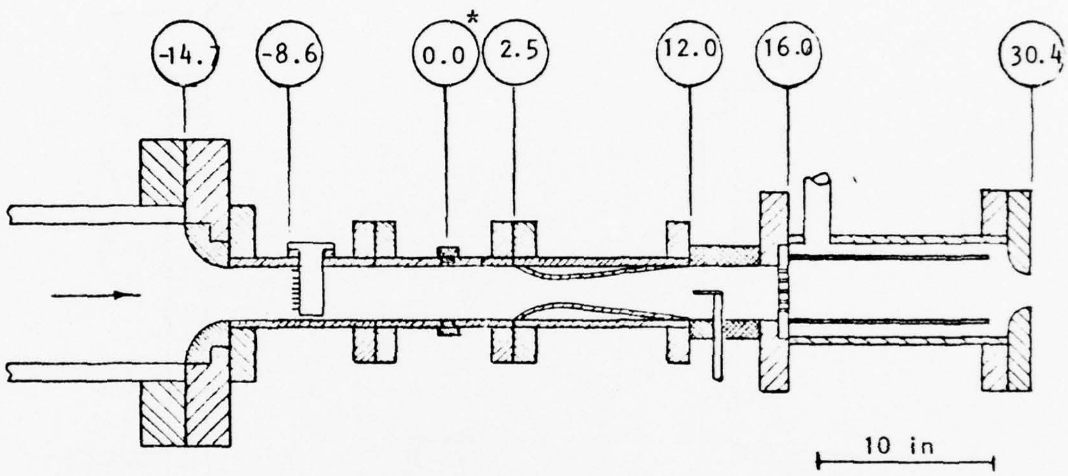


Figure 5. Design Concept C - Air Assist Atomizer



*Station numbers represent distances measured downstream from the fuel injection station, in inches

Figure 6. Carburetion System Test Apparatus

SECTION III

PRELIMINARY SCREENING TESTS

The first of the series of screening tests consisted of operation of each candidate design at condition 1 to determine whether flashback or auto-ignition would occur. Design candidates passing this test would then be tested at conditions 2, 5 and 10 to measure fuel distributions, degree of vaporization and velocity profiles.

Operation of the three candidate designs at condition 1 produced mixed results. In all cases, a temperature rise of from $200^{\circ}R$ to $400^{\circ}R$ was registered by the downstream thermocouples during the fuel injection sequence. This temperature rise was detected independent of whether the downstream combustor was operating, indicating an autoignition phenomenon. Inspection of the flameholder plate after these tests revealed a heat discoloration in a circular region approximately 1-inch in diameter, located at its center. Based on this evidence, it would appear that a small region of the flow in the central region of the duct was able to autoignite. The fuel injection section in designs A and C showed no evidence of burning. However, the fuel shear blades of design B showed a pronounced deposit of soft carbon along the downstream section of the blade as illustrated in Figure (7). Attempts to relieve this apparent burning around the blades by altering the fuel injection pattern produced no observable effect. Based on these results, the air blast concept (design B) was discarded from further consideration.

Fuel distribution surveys were made for designs A and C at test conditions 2, 5 and 10, the results of which are presented in Figures (8) and (9). Several comments can be made at this point which pertain equally to both designs. First, and most important, the fuel distribution is poor with a pronounced peak in concentration occurring near the axis (the region where some degree of combustion is evidently taking place). Second, conditions 2 and 10, which differ only in the air velocity (100 and 125 fps, respectively) produce profiles which are quite similar whereas condition 5, where the air temperature drops by $150^{\circ}F$, tends to produce a broader region of high fuel concentration.

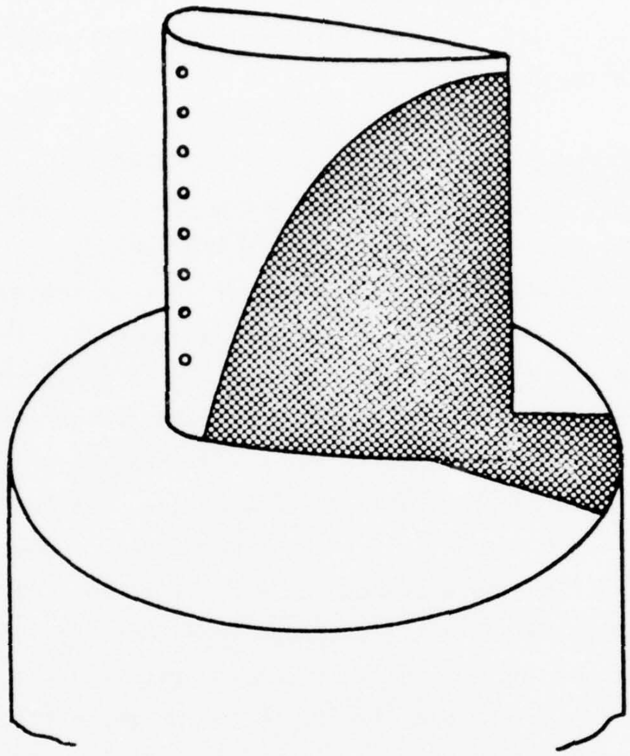


Figure 7. Carbon Deposition Pattern on Air Blast Blade

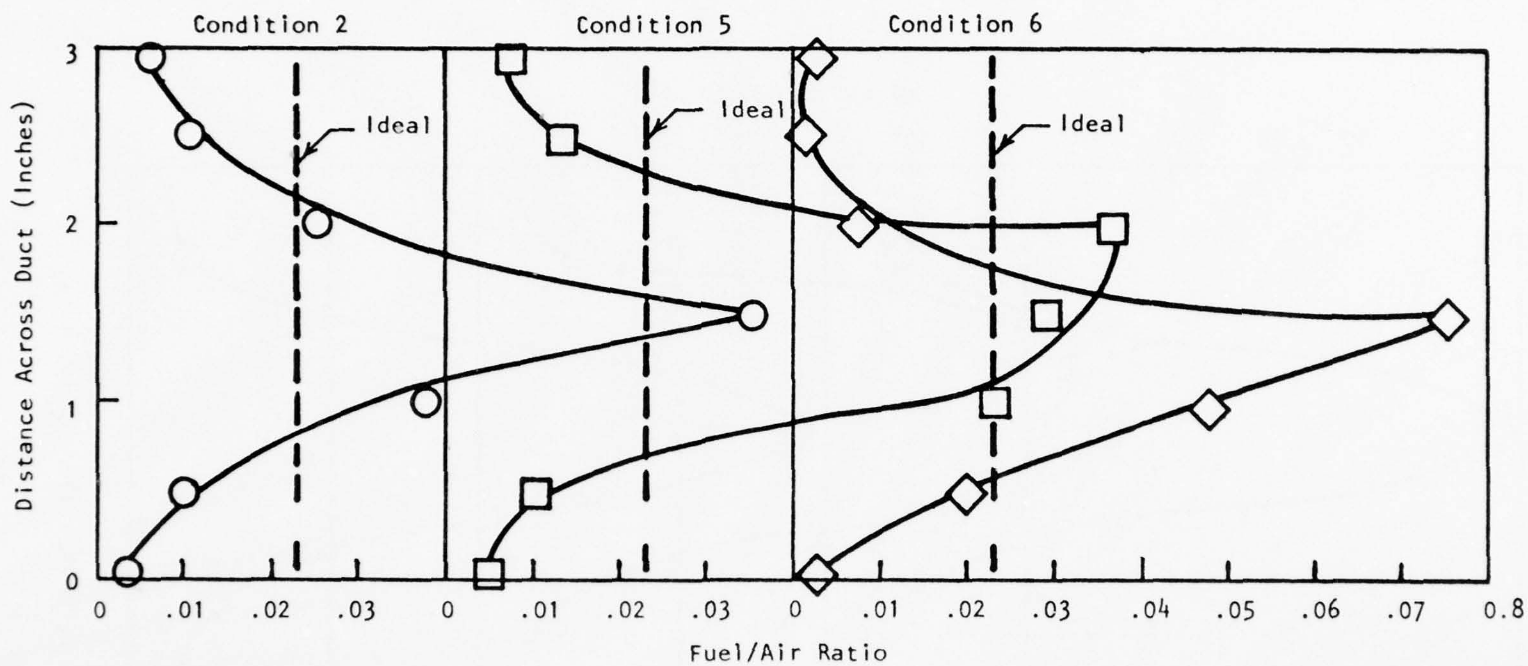


Figure 8. Fuel Distribution Profiles Obtained with Design Concept A (Pressure Atomization)

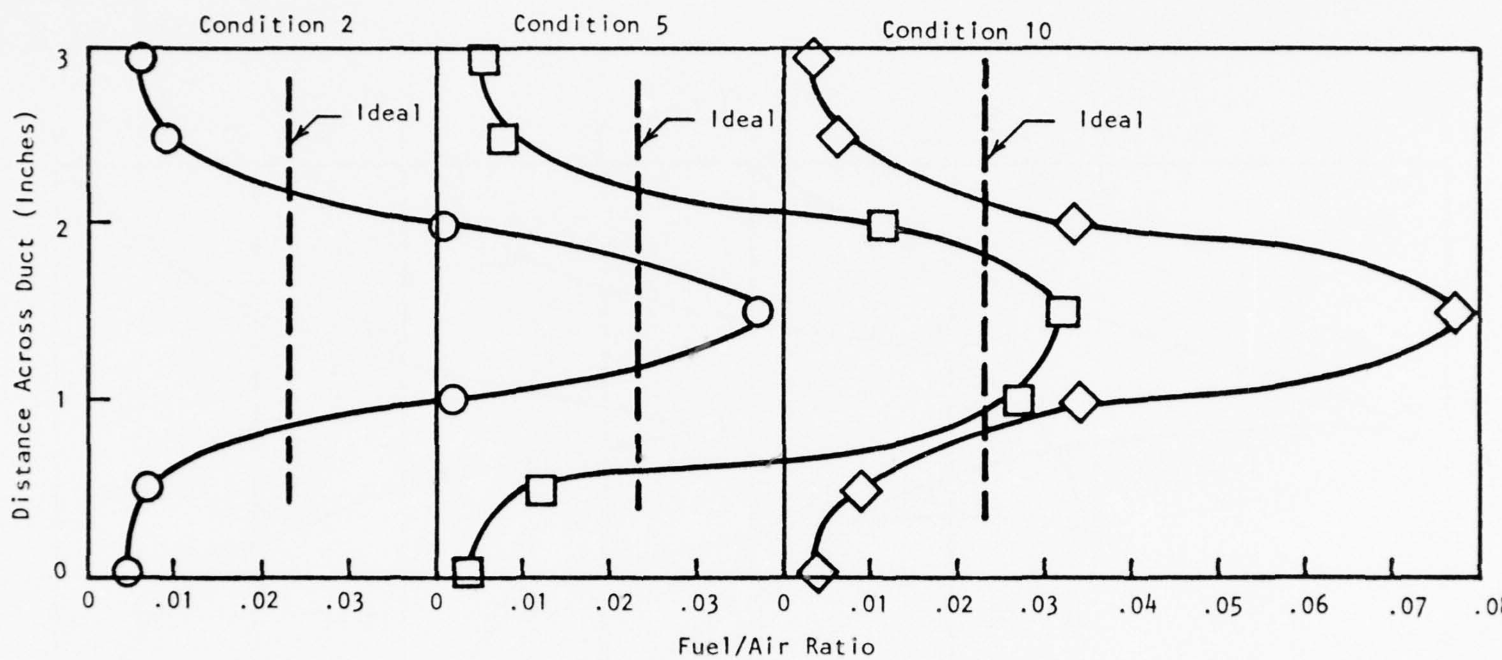


Figure 9. Fuel Distribution Profiles Obtained with Design Concept C (Air Blast Atomization)

Therefore, an absolute temperature change of 11% produces a far more noticeable effect than that produced by a velocity change of 25%.

The principal difference between the two designs is the lack of symmetry displayed by the pressure atomization design. For the case of the air-assist atomization design, the high central fuel concentration is understandable and can be rationalized on the basis of the low momentum/drag ratio of the fine fuel droplets which causes them to be swept downstream before they achieve significant lateral penetration. In the pressure atomization case, the high central fuel concentration is somewhat surprising and indicates that the fuel jets are remaining relatively coherent until after they are turned downstream by the airflow. In this case, jet penetration criteria are not, by themselves, useful as a design guide.

SECTION IV

DESIGN MODIFICATION FOR PERFORMANCE IMPROVEMENT

The high central fuel concentrations produced by the pressure and air-assist atomization designs (A and C) are similar to those reported in Reference (5) where a single centrally-mounted air blast nozzle was employed. In that instance, the use of air swirl was shown to be an effective mechanism to bias the fuel distribution toward the walls. Following this approach, swirl generators were installed in the A and C designs as illustrated in Figures (10) and (11) and a series of tests were run to determine the effect of air swirl angle on the exit plane fuel distribution profile. The results of these tests are summarized in Figure (12).

In general, it can be seen that the addition of swirl to the airflow causes the fuel distribution to be biased toward the wall; an effect which is to be expected where liquid droplets are present. However, whereas the fuel distributions obtained using the air-assist atomizer are symmetric, displaying a consistent trend with swirl angle, those obtained with the pressure injection design are asymmetric and display a seemingly inconsistent trend with swirl. This behavior of the pressure atomizing design indicates a lack of circumferential uniformity with peaks in fuel concentration corresponding to the discrete injection ports. The addition of swirl to this system not only biases the initial droplet distribution, but also causes the profile to be rotated at the exit plane. The circumferential asymmetry displayed by this design made it appear less promising in the present application than the air-assist design concept.and it was dropped from further consideration.

For the air-assist atomization design, one can see a steady decrease in centerline fuel concentration with increasing air swirl angle, accompanied by a corresponding increase in concentration near the walls. Unfortunately, none of the swirl angles tested produced an entirely satisfactory profile since the amount of swirl necessary to flatten the profile near the centerline produces an undesirable excess of fuel near the walls and the swirl angle which produces a flat profile near the walls results in an excessive fuel concentration near the axis. A potential solution to this problem lies in the use of

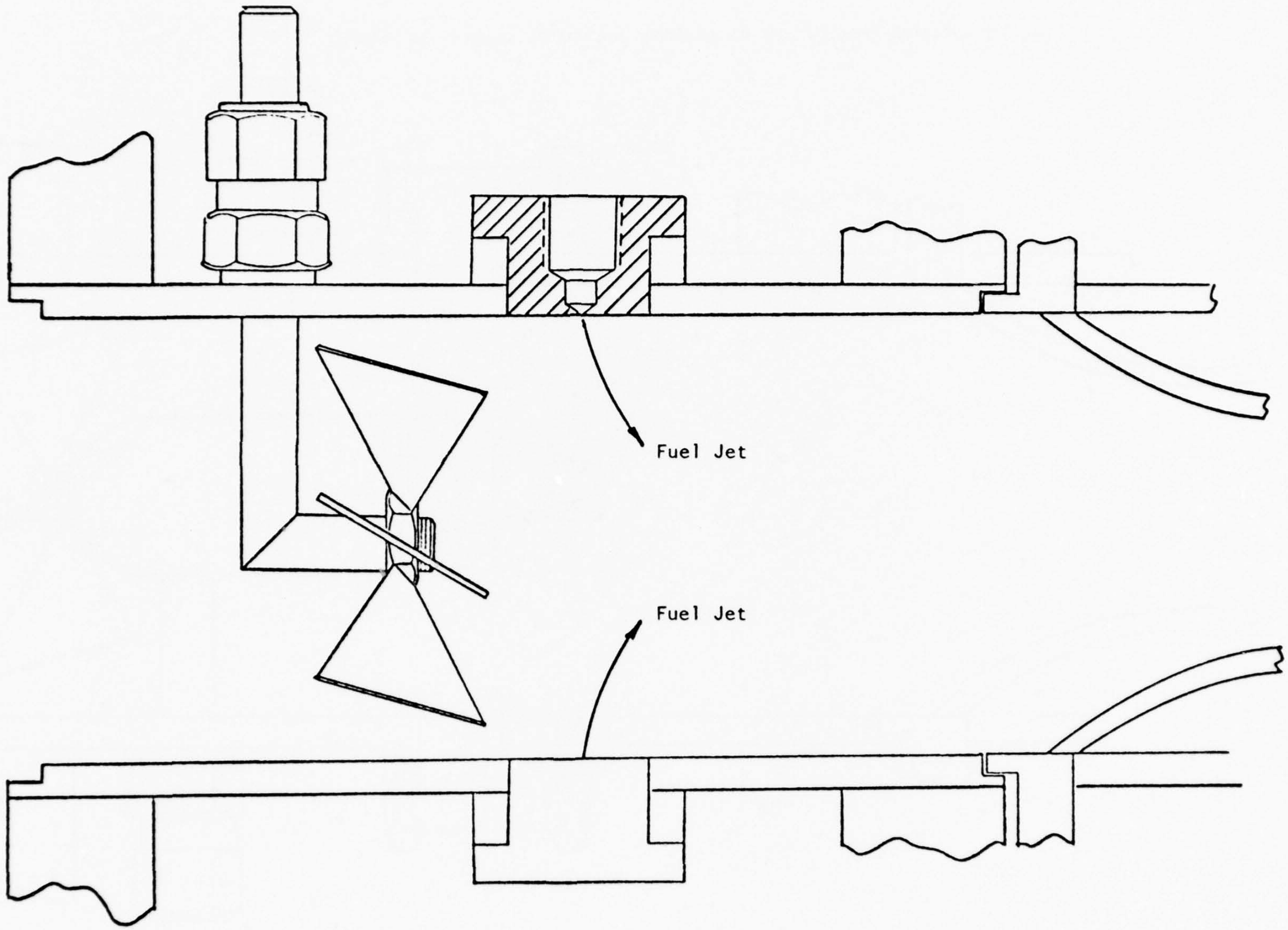


Figure 10. Swirl Generator Mounted in Pressure Atomization Design

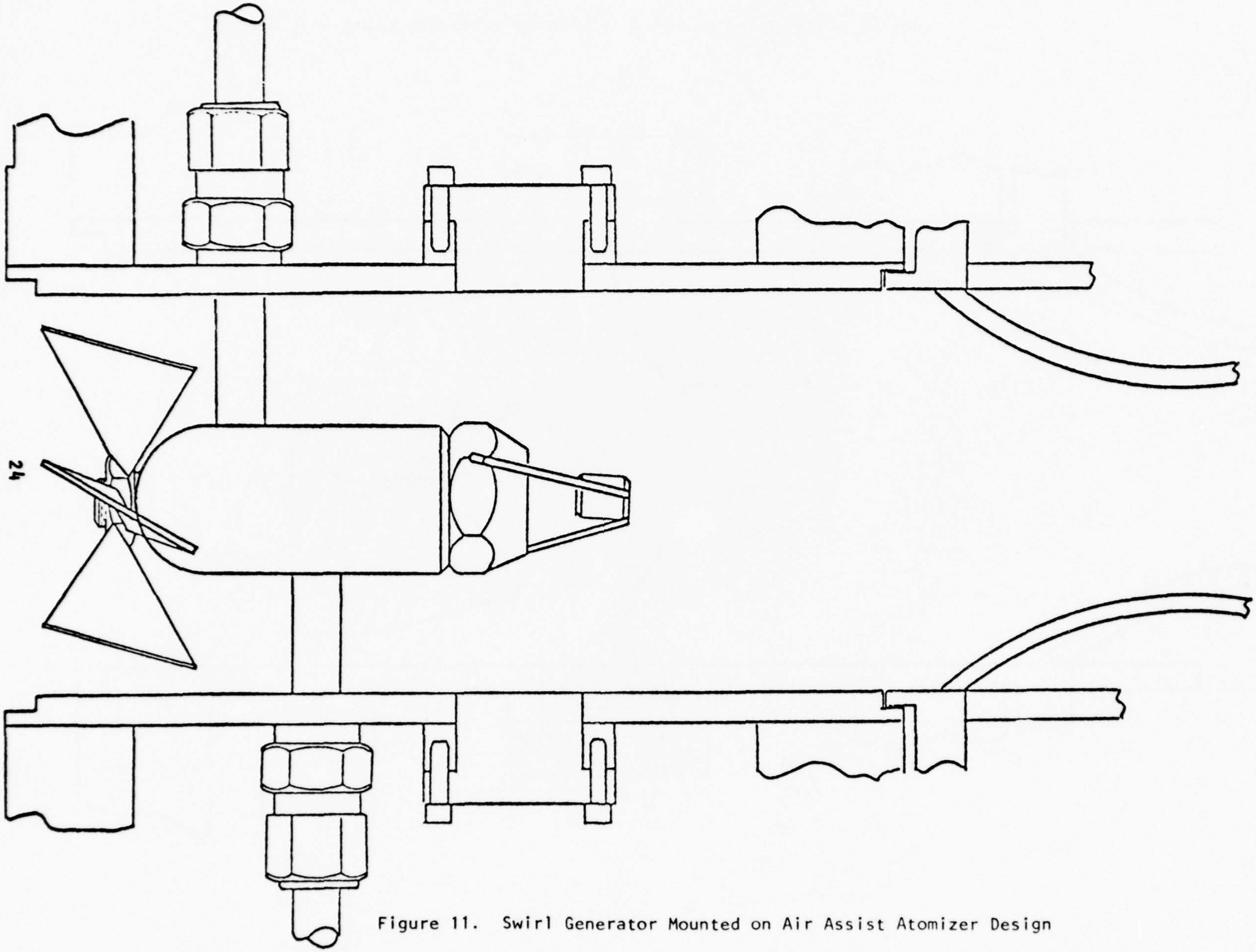
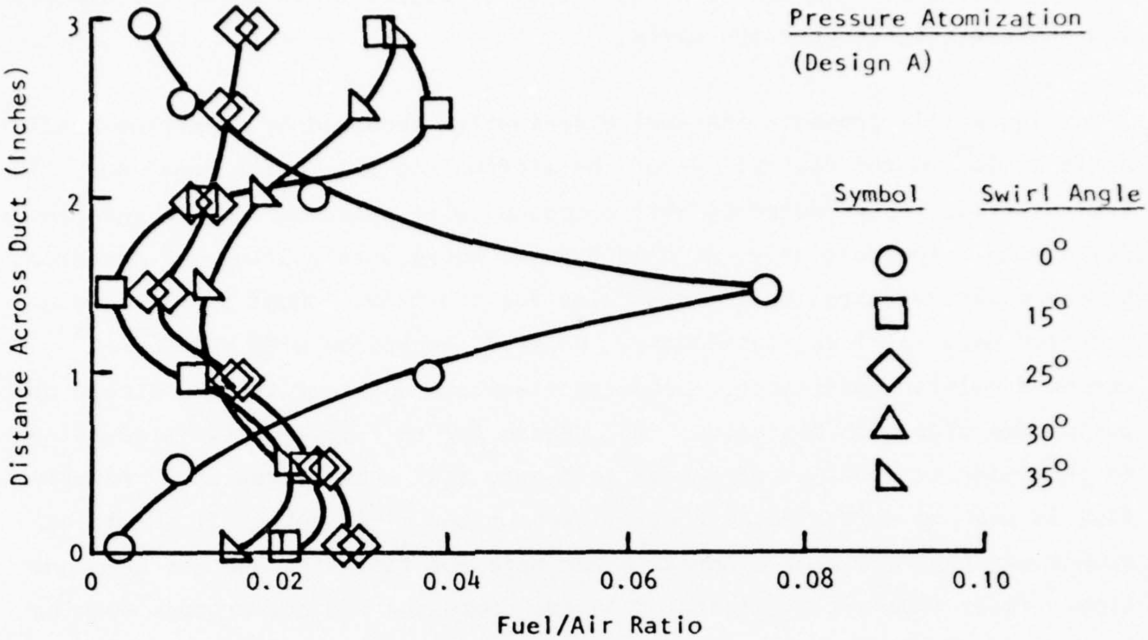


Figure 11. Swirl Generator Mounted on Air Assist Atomizer Design



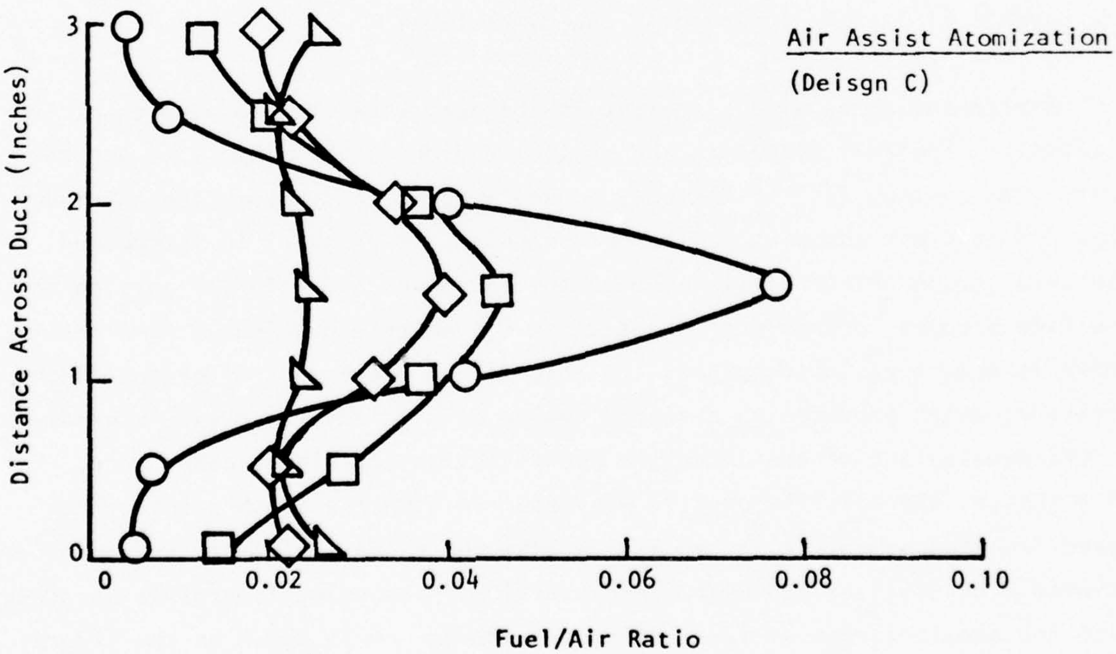


Figure 12. Fuel/Air Distributions as a Function of Air Swirl/ Angle (Design Concepts A and C at Condition 2)

variable air swirl angle, employing a greater degree of swirl at the center and a lesser degree near the walls.

Figure (13) presents the fuel distribution produced by imparting a swirl angle of 60^{o} to the central 50% of the airflow and 30^{o} to the remainder. The fuel distribution produced by this compound swirl generator can be seen to be quite good. Interestingly, at condition 1, where autoignition was detected by the mixer exit station thermocouples for the flow without swirl, none was detected once swirl was introduced. However, operation with the $30^{o}/60^{o}$ compound swirler consistently produced flashback whenever the downstream combustor was placed in operation. The reason for this difficulty is revealed in the velocity profiles presented in Figure (14) where a region of reverse flow is seen to exist in the central area of the mixer tube. It should be emphasized that the problem experienced here was flashback and not autoignition. Tests made with no ignition in the combustor did not produce burning in the mixer. Rather, upstream combustion was encountered only when the combustor was put in operation. It is not surprising to see that the combustion products which are convected upstream by the strong recirculating flow field are capable of causing ignition in the mixer tube.

Recirculation is always present in the near wake of a body, such as the air-assist atomizer, placed in the central region of the mixer tube and results from an inability of the body boundary layer to overcome the adverse pressure gradient associated with body closure. When swirl is introduced, the axial component of airstream momentum decreases and a larger portion of the flow becomes incapable of negotiating the adverse gradient. As a result, there is some question regarding the role of the convergent-divergent flash arrestor, which produces an extended region of mild adverse pressure gradient, on the development of the extensive recirculation zone in evidence here. For this reason, the velocity profile was measured with the flash arrestor removed from the mixer. Although Figure (14) shows the profile to be improved, reverse flow still exists near the centerline. The velocity profile obtained with the atomizer removed from the system (design A) is shown on the figure to provide a base of reference.

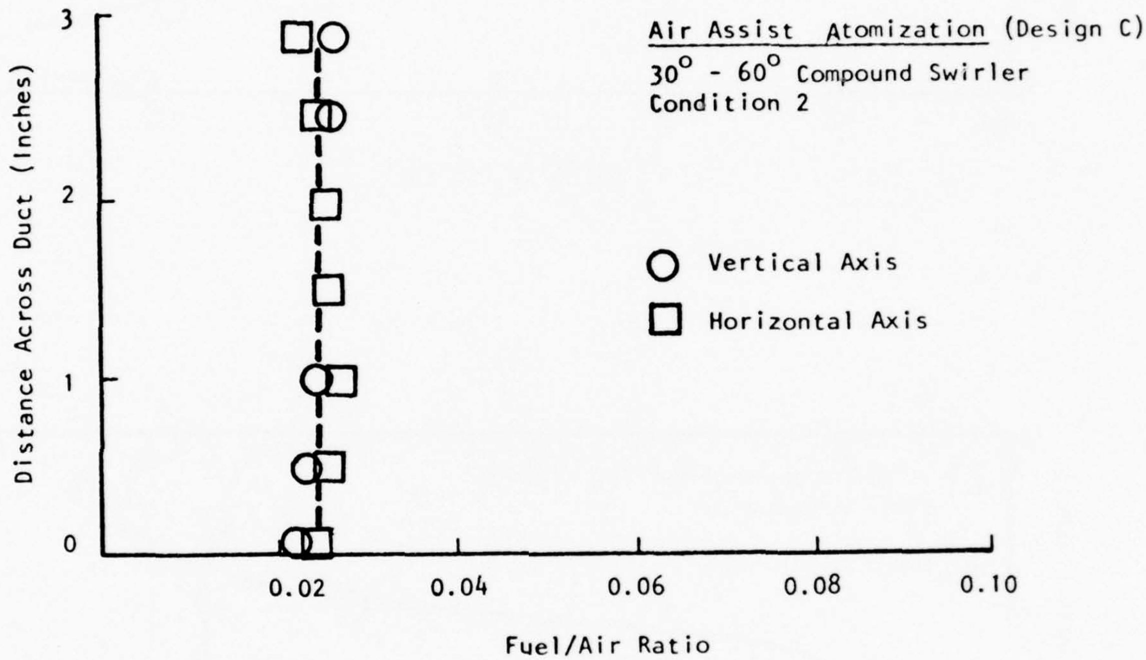
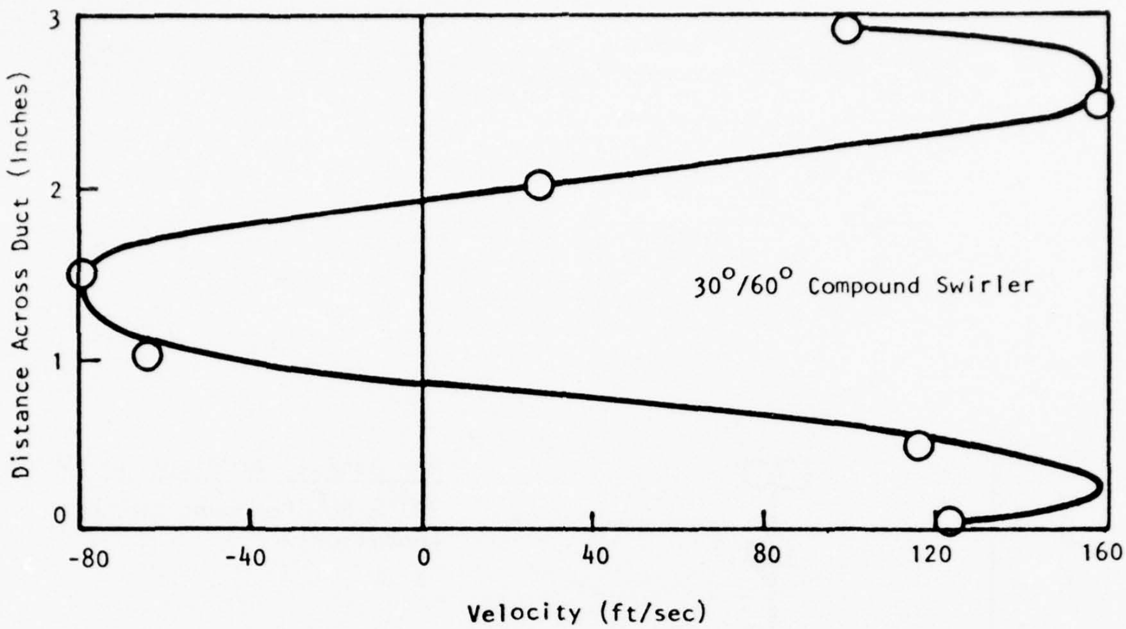


Figure 13. Fuel/Air Distribution Produced by a $30^{o}/60^{o}$ Compound Swirler (Design Concept C at Condition 2)



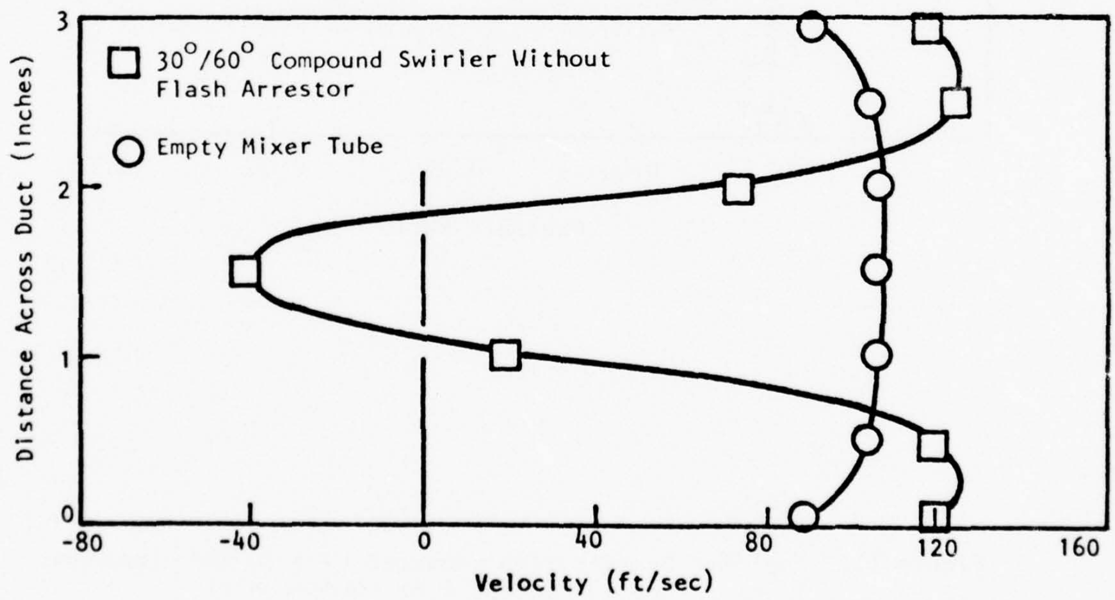


Figure 14. Velocity Profiles with 30°/60° Compound Swirler (Design C at Condition 2)

Clearly, a negative velocity anywhere in the mixer exit plane cannot be tolerated since this will produce flashback. However, even a small positive velocity fails to meet the performance criterion of small exit velocity perturbations. Therefore, since swirl has been found to be a positive mechanism for improving fuel distribution, and compound swirl provides increased flexibility, it remains to find a compromise swirl distribution which will provide acceptable fuel and velocity distributions simultaneously. A series of tests were performed with varying swirl angle distributions, the results of which are presented in Figure (15). The velocity profile is seen to exhibit extreme sensitivity to swirl angle in the central region. The velocity near the wall appears to be less sensitive to swirl, but velocity levels near the wall are disturbingly low, posing a potential problem with regard to autoignition and flashback. Since low wall velocities are indicative of limited flow separation in the flash arrestor, one would expect to find higher velocities further downstream. Figure (16) presents the velocity profile measured at the original mixer exit plane (12-inches downstream of the injection station) and at a station 6-inches further downstream using a $25^{\circ}/40^{\circ}$ compound swirler. The central region velocity profile is seen to flatten very slightly. However, there is a marked improvement in the wall velocity levels, eliminating the flashback/autoignition objection.

In all tests, the fuel was found to be completely vaporized by the flash arrestor exit, 12-inches downstream of the injection station, a finding consistent with similar results reported in References (5) and (6).

Based on the results of these tests, and a tradeoff between velocity and fuel distributions in the mixer exit plane, the final configuration was fixed as consisting of the air-assist atomizer with a $25^{\circ}/40^{\circ}$ swirl generator mounted in the original twelve inch mixer tube with a six-inch extension spool added on the downstream end. The final configuration (design C-1) is illustrated in Figure (17).

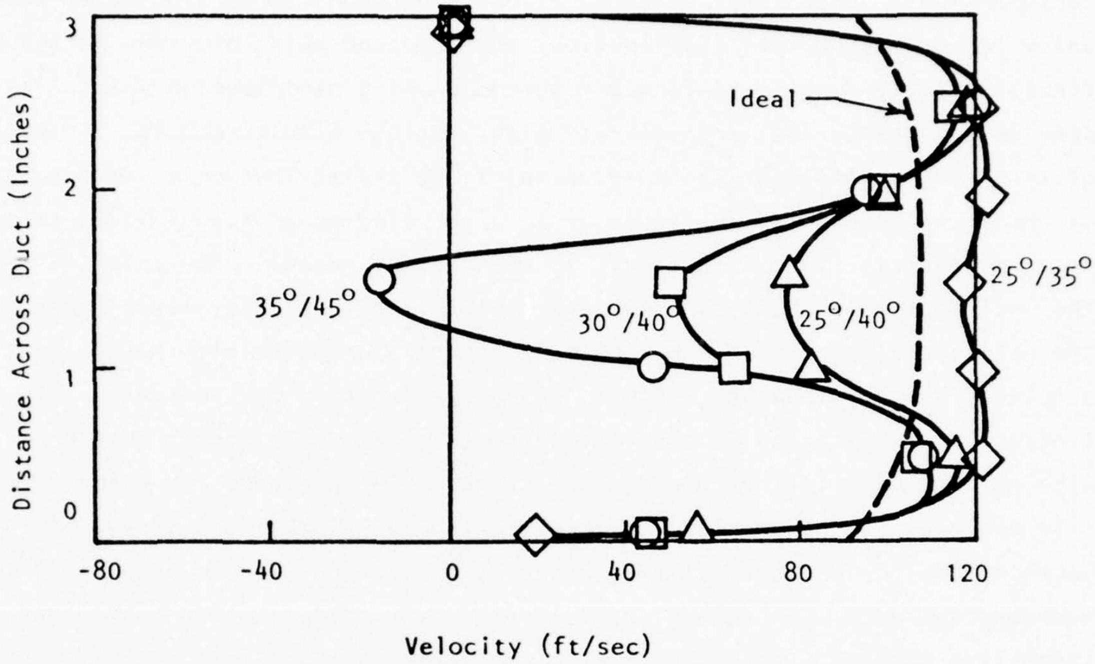


Figure 15. Velocity Distributions for Various Swirl Generator Combinations (Design C at Condition 2)

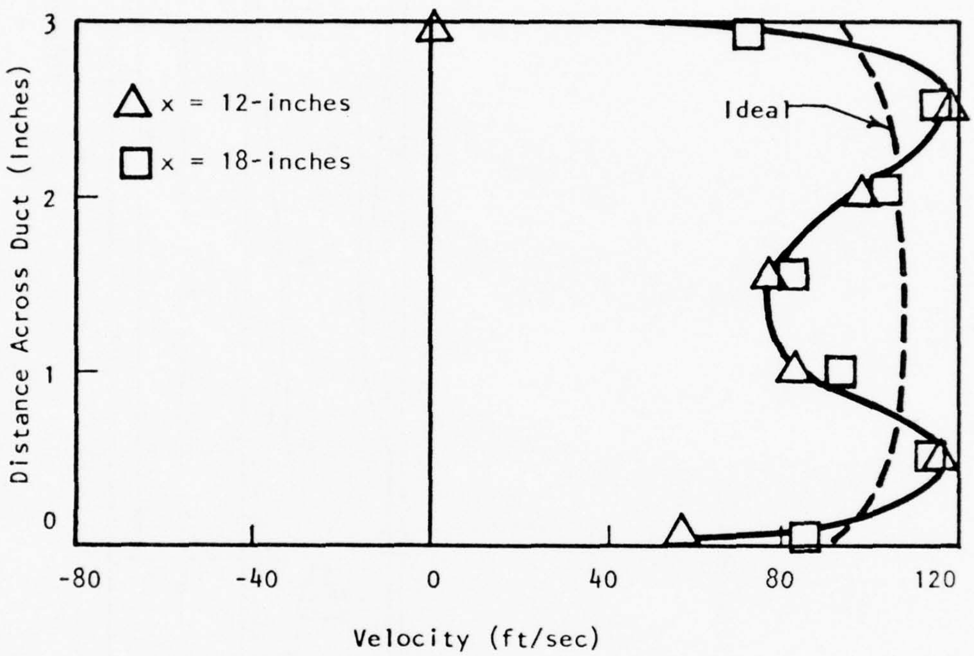


Figure 16. Exit Plane Velocity Distribution For Design With a Six Inch Extension (Design C-1)

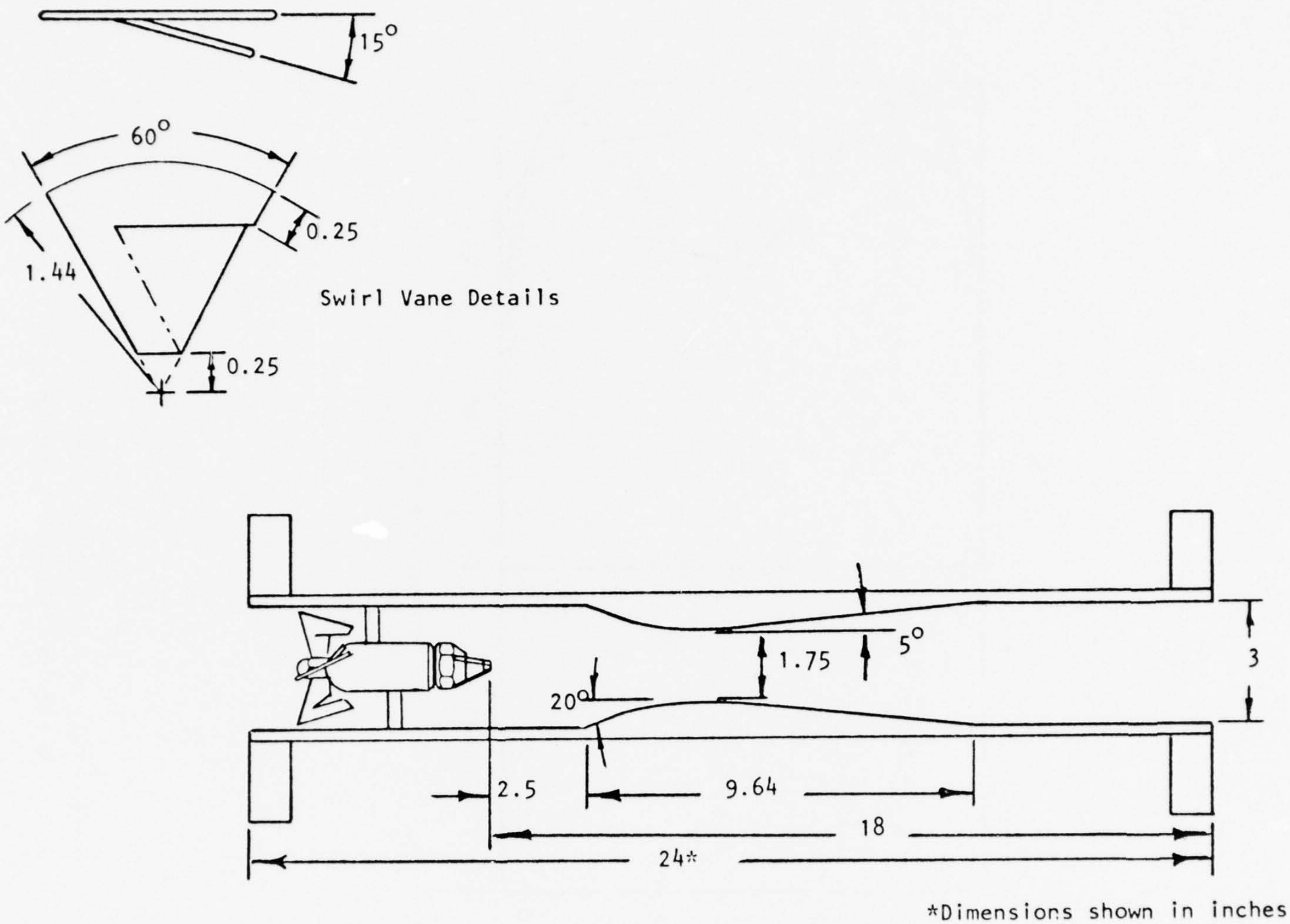


Figure 17. Final Configuration (Design C-1)

SECTION V

FULL PERFORMANCE CHARACTERIZATION

Having fixed the geometry of the fuel/air carburetion system, a series of tests were run to measure fuel, velocity and phase distributions at the exit plane and at an intermediate plane located 75% of the distance from the injector to the exit. Tests were run at each of the ten operating conditions listed in Table I (although only autoignition/flashback data was taken at condition 1). Preliminary tests indicated a sensitivity of exit plane fuel distribution profile to certain operating conditions, notably low temperature. Under these conditions, where droplet lifetimes were increased, the fixed air swirl distribution produced a stronger centrifugal bias. This undesirable sensitivity was found to be remediable by varying the atomizing air pressure differential (flow rate) so as to reduce the initial droplet size under conditions where evaporation times increase. Therefore, since it is desirable to introduce atomizing air pressure as an operating variable, all data was taken while varying this quantity parametrically.

As stated earlier, the fuel was found to be entirely in the gas phase for all operating conditions, both at the exit plane (x = 18-inches) and at the intermediate station (x = 13.5-inches). Velocity distributions measured at the intermediate and exit planes are presented in Figures (18) and (19) respectively. The velocity distributions display little sensitivity to operating conditions, scaling with mean velocity level. Distributions measured in the horizontal and vertical planes indicate a symmetric flow with only moderate deviations from the ideal case (defined as the empty mixer tube configuration). The standard deviation of the velocity and fuel distributions from the ideal case is a convenient measure of the merit of the carburetion system performance. For the exit plane velocity profiles presented in Figure (19), the overall standard deviation from the ideal distribution is 10.5%.

The fuel distribution profiles at conditions 2 through 10 are presented in Figures (20) and (21) for atomizing air pressure differentials of 8, 16 and 24 psi. In all cases but two, the lowest atomizing air pressure differential (8 psi) is seen to produce the best fuel distribution.

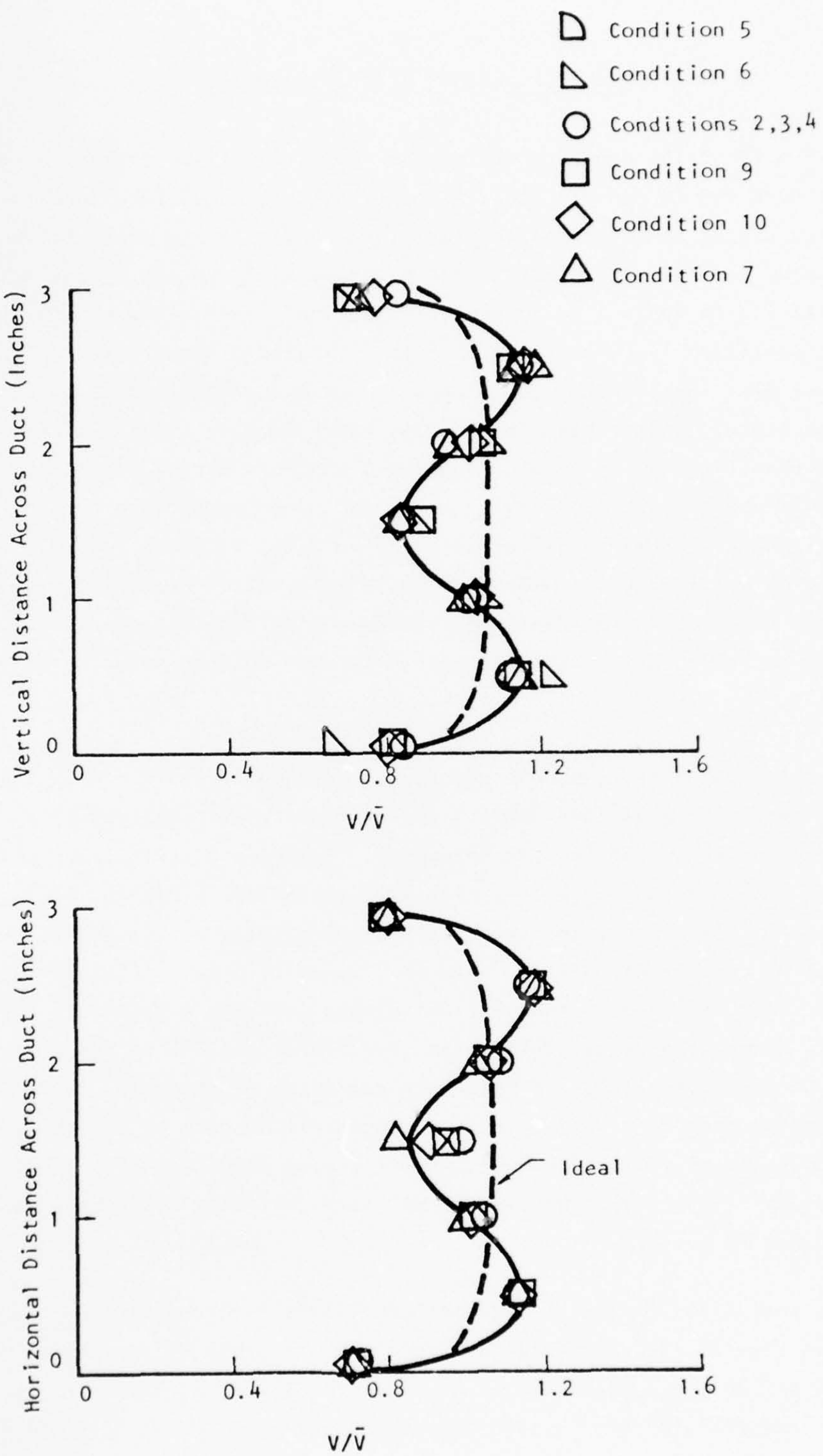


Figure 18. Velocity Distributions at Station 13.5

α ≡ RMS Deviation

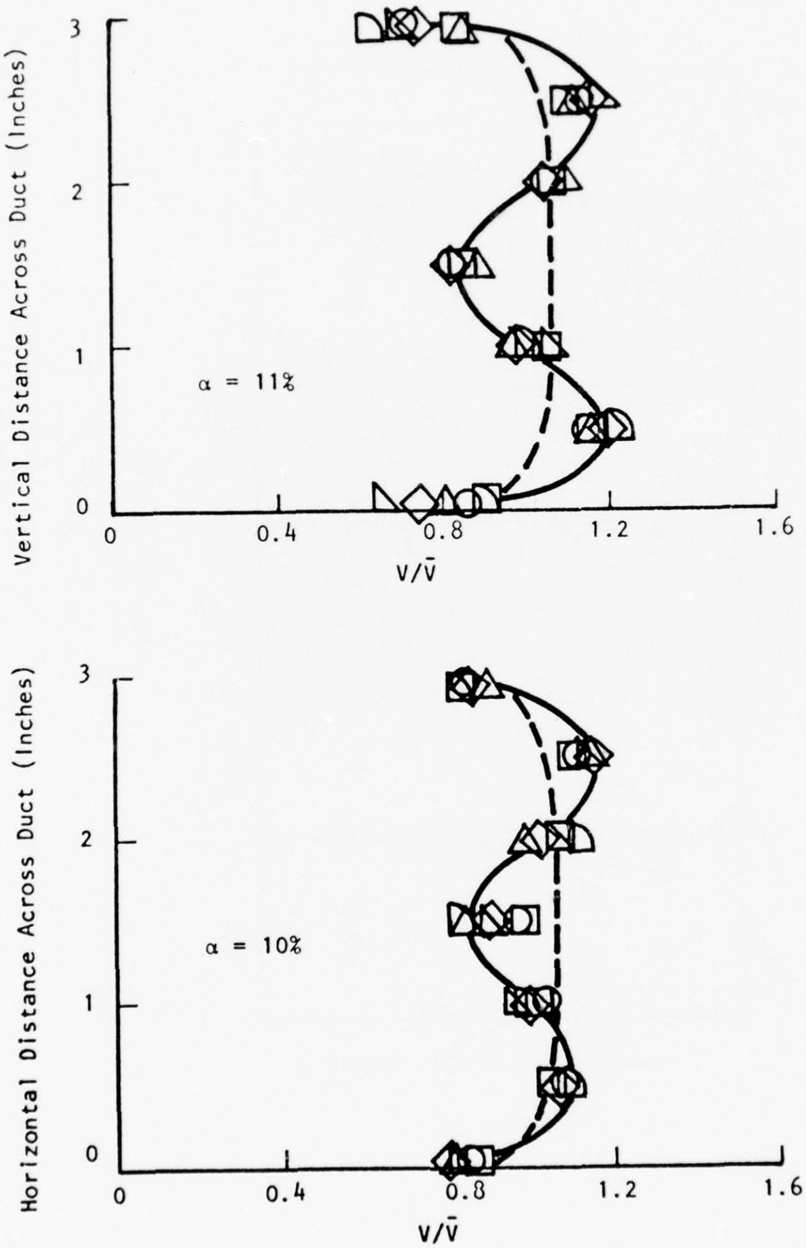


Figure 19. Velocity Distributions at Station 18.0

Note: Circular and diamond symbols represent horizontal and vertical axes, respectively.

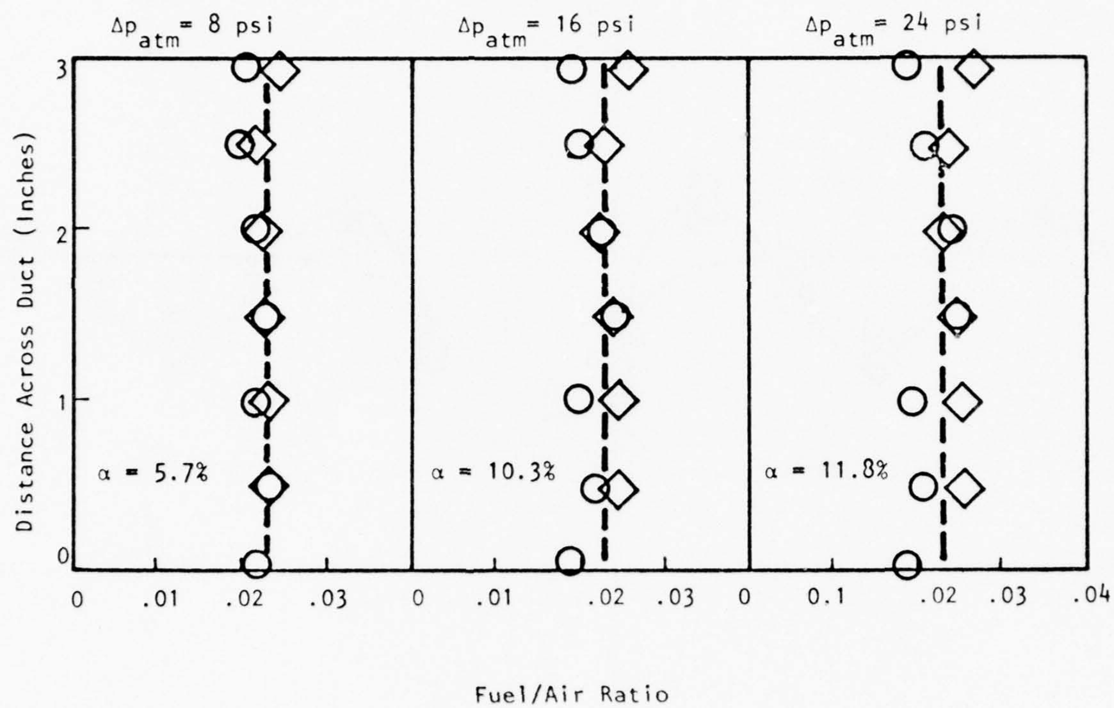


Figure 20a. Fuel Distribution Profiles at Station 18.0 (Condition 2)

Note: Circular and diamond symbols represent horizontal and vertical axes, respectively.

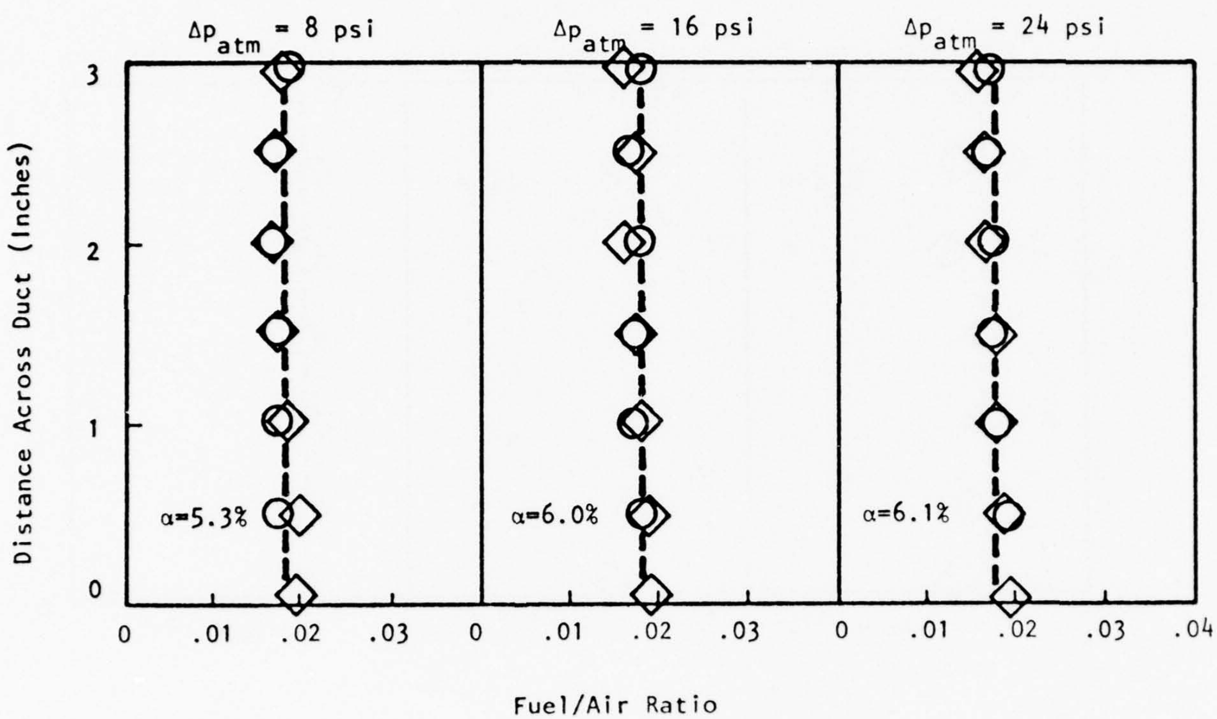


Figure 20b. Fuel Distribution Profiles at Station 18.0 (Condition 3)

Note: Circular and diamond symbols represent horizontal and vertical axes, respectively.

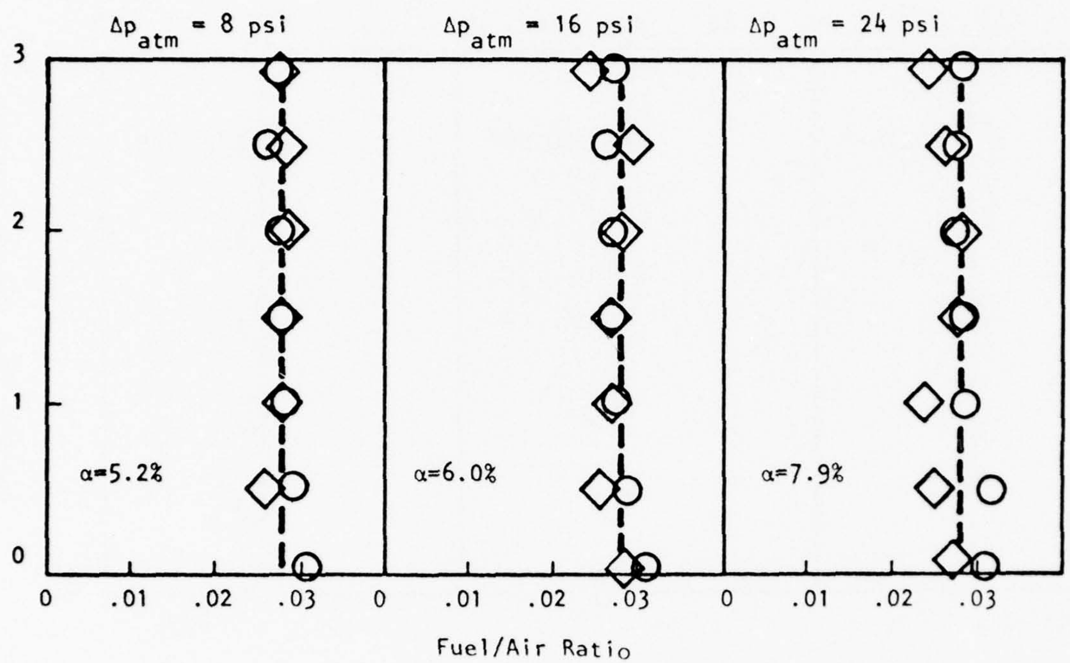


Figure 20c. Fuel Distribution Profiles at Station 18.0 (Condition 4)

Note: Circular and diamond symbols represent horizontal and vertical axes, respectively.

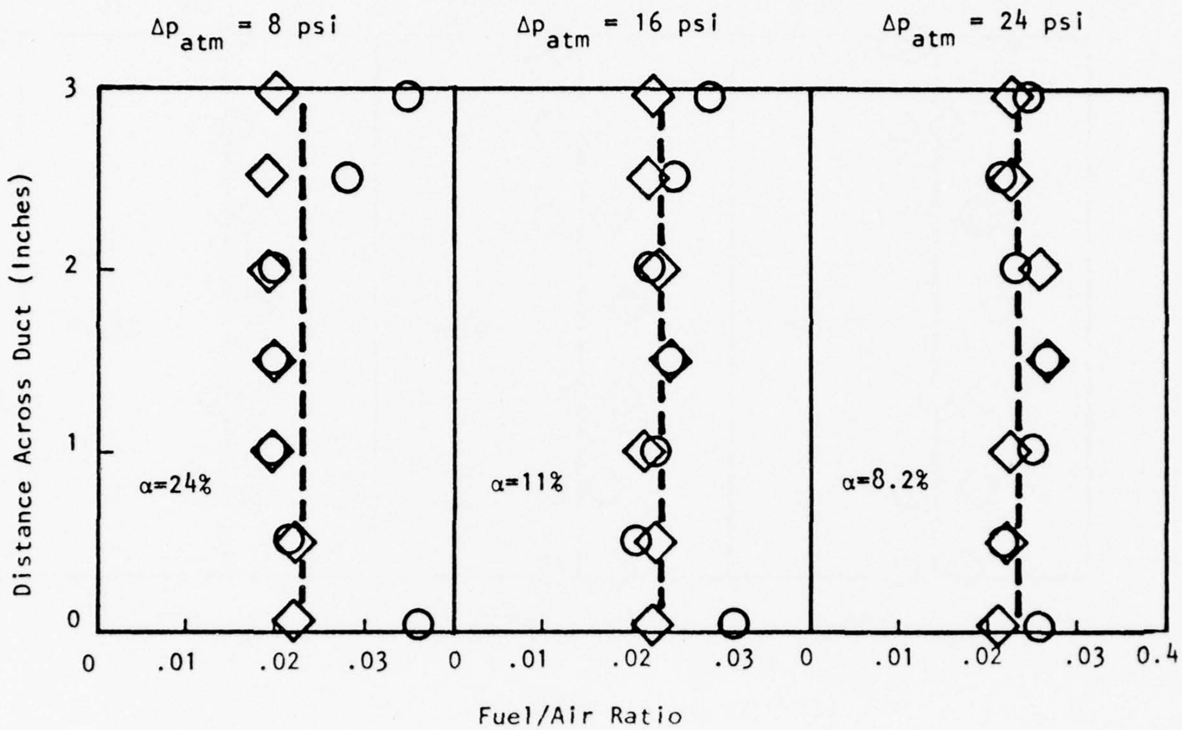


Figure 20d. Fuel Distribution Profiles at Station 18.0 (Condition 5)

Note: Circular and diamond symbols represent horizontal and vertical axes, respectively.

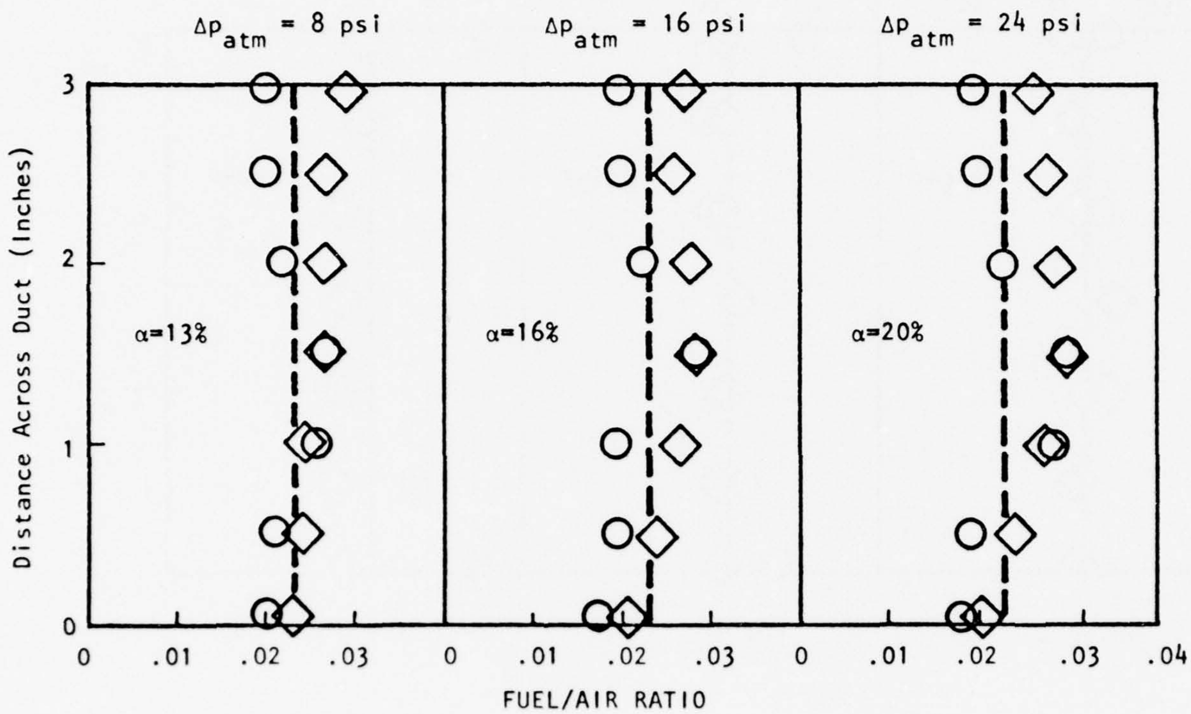


Figure 20e. Fuel Distribution Profiles at Station 18.0 (Condition 6)

Note: Circular and diamond symbols represent horizontal and vertical axes, respectively

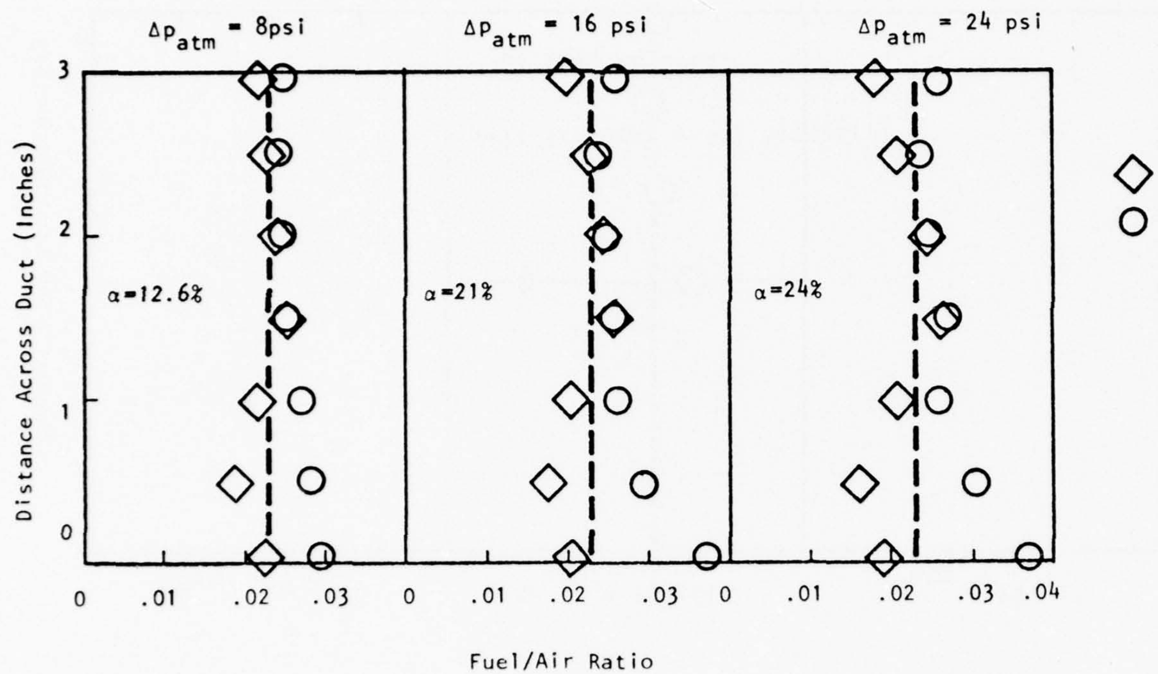


Figure 20F. Fuel Distribution Profiles at Station 18.0 (Condition 7)

Note: Circular and diamond symbols represent horizontal and vertical axes, respectively.

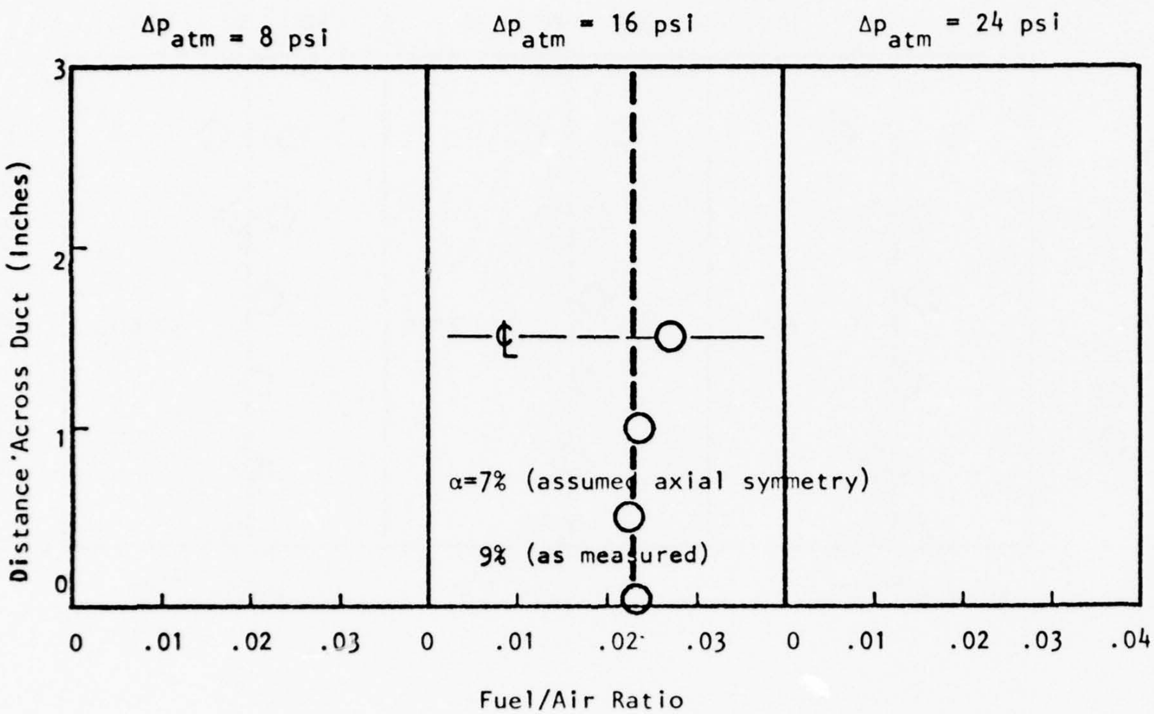


Figure 20g. Fuel Distribution Profiles at Station 18.0 (Condition 8)

Note: Circular and diamond symbols represent horizontal and vertical axes, respectively.

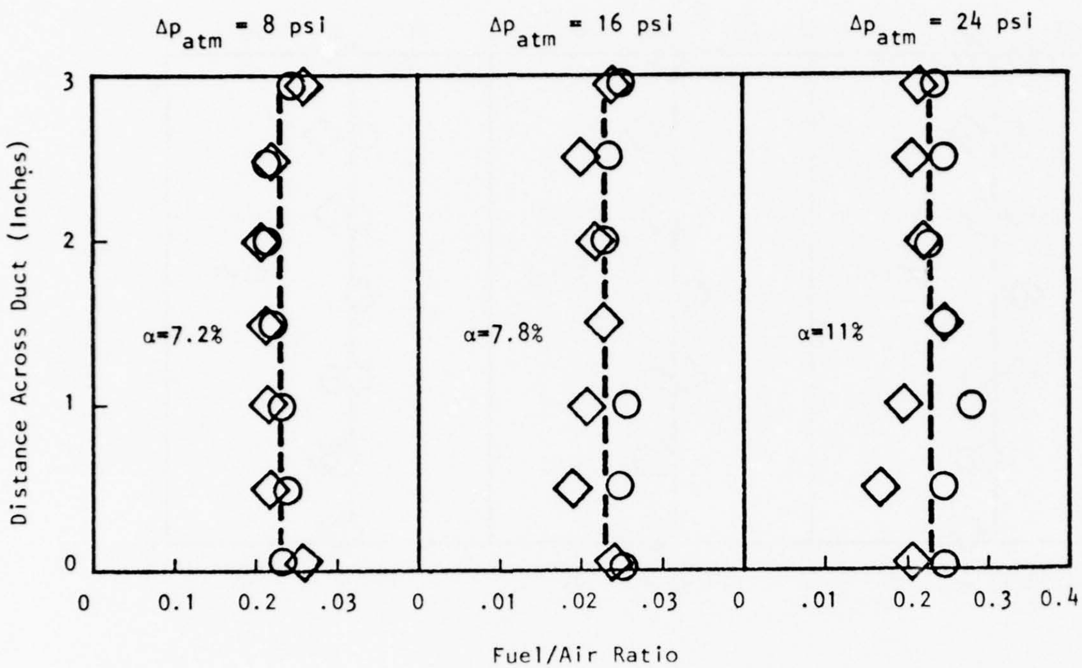


Figure 20h. Fuel Distribution Profiles at Station 18.0 (Condition 9)

Note: Circular and diamond symbols represent horizontal and vertical axes, respectively.

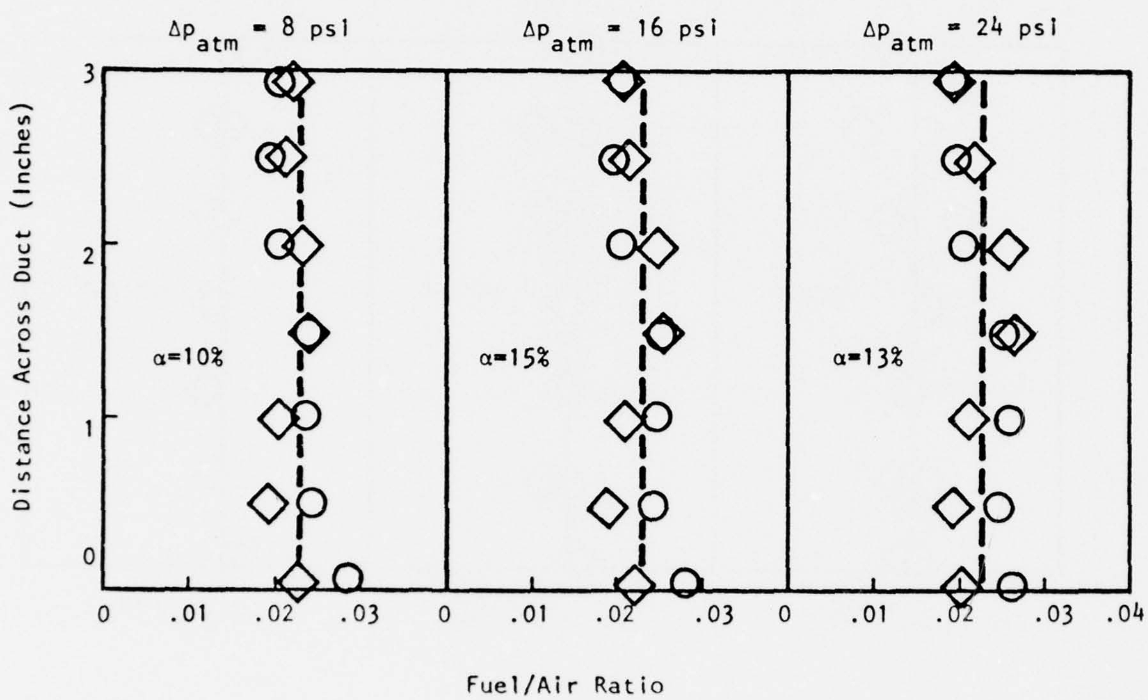


Figure 20i. Fuel Distribution Profiles at Station 18.0 (Condition 10)

Note: Circular and diamond symbols represent horizontal and vertical axes, respectively.

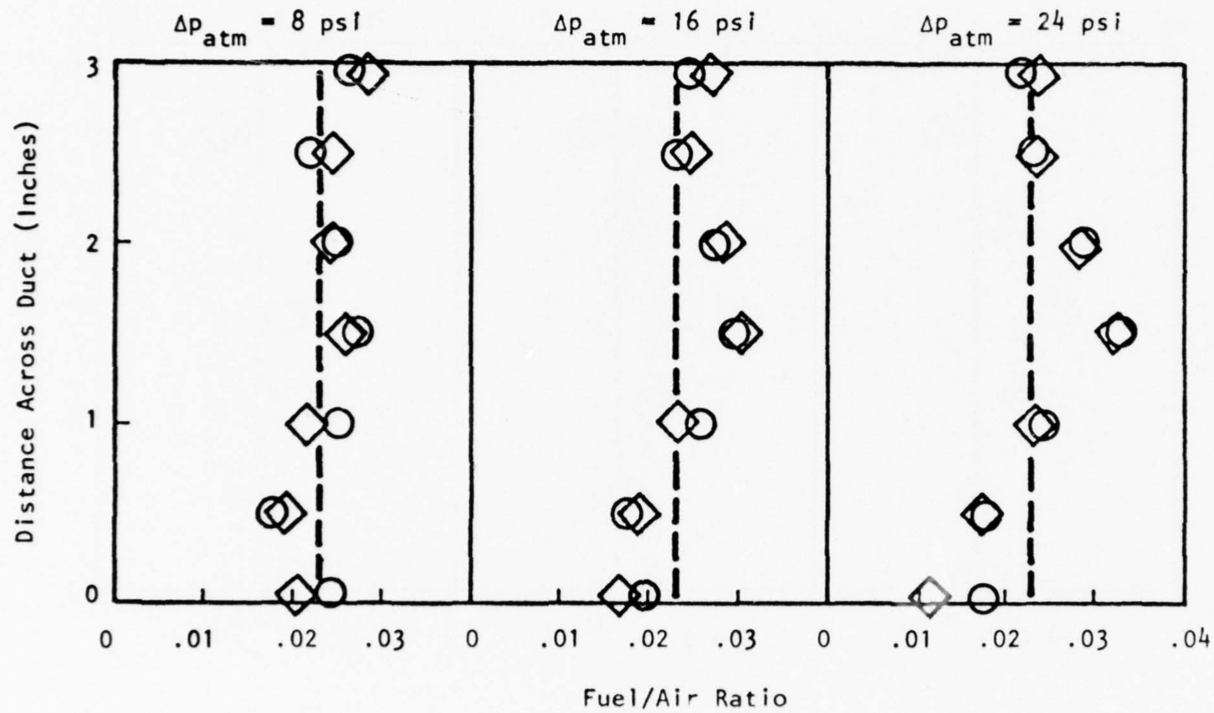


Figure 21a. Fuel Distribution Profiles at Station 13.5 (Condition 2)

Note: Circular and diamond symbols represent horizontal and vertical axes, respectively.

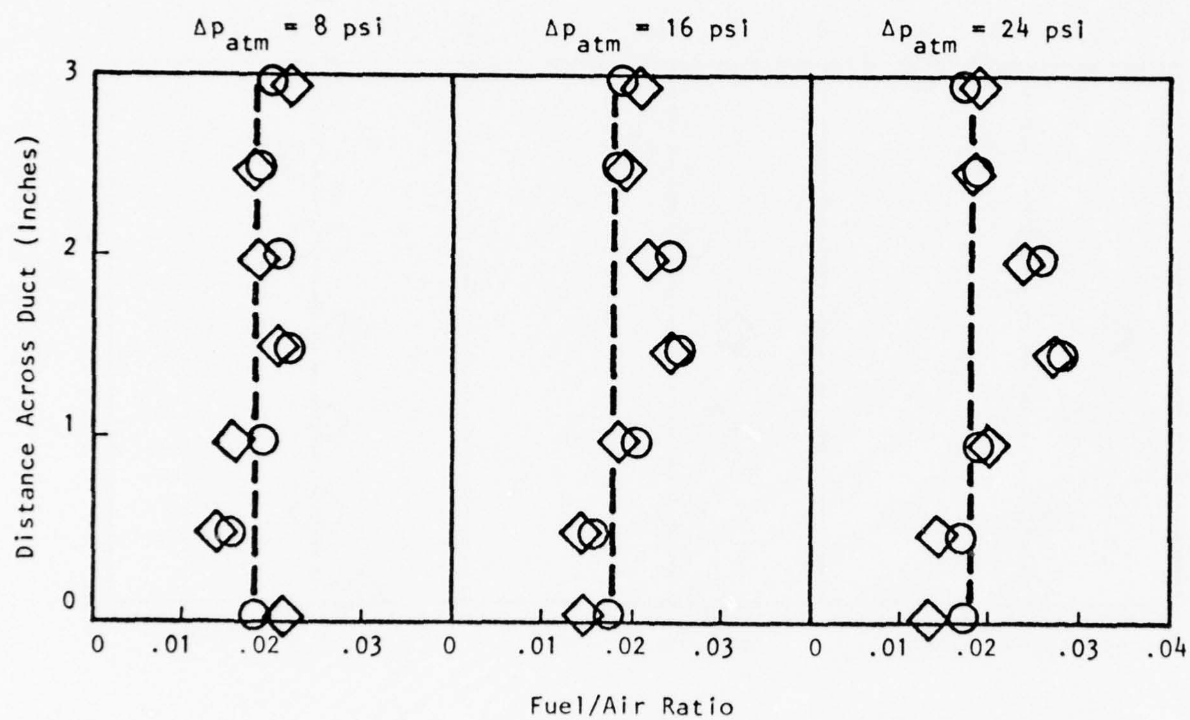


Figure 21b. Fuel Distribution Profiles at Station 13.5 (Condition 3)

Note: Circular and diamond symbols represent horizontal and vertical axes, respectively.

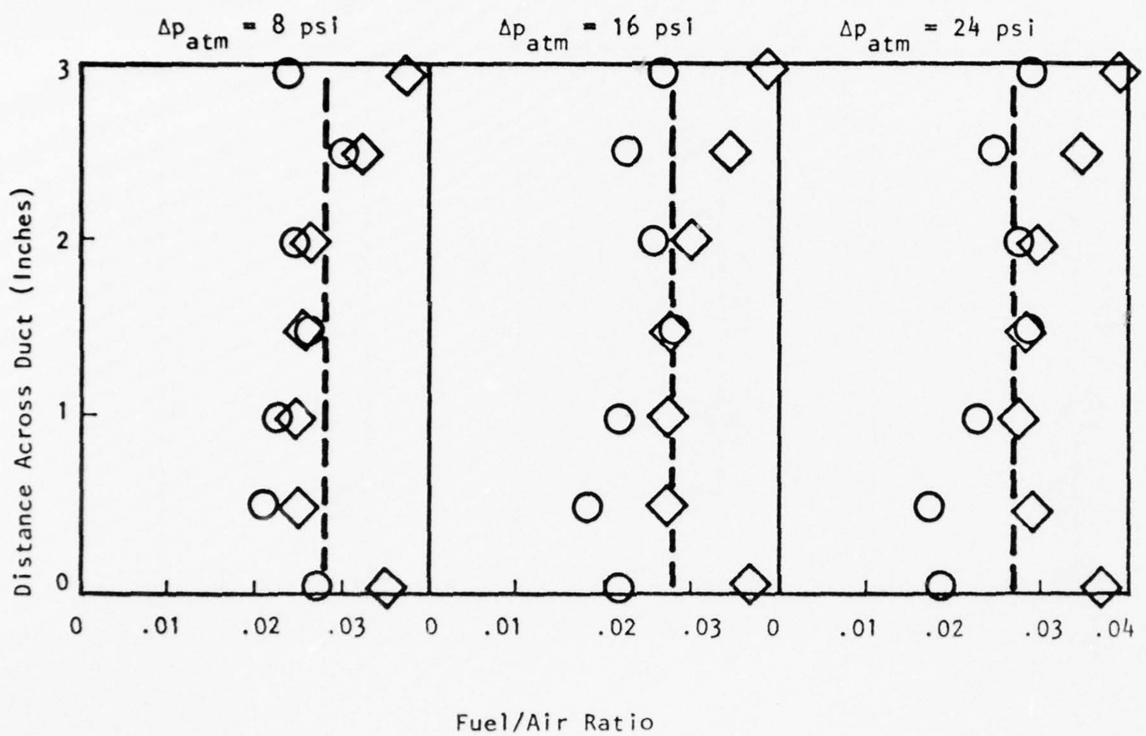


Figure 21c. Fuel Distribution Profiles at Station 13.5 (Condition 4)

Note: Circular and diamond symbols represent horizontal and vertical axes, respectively.

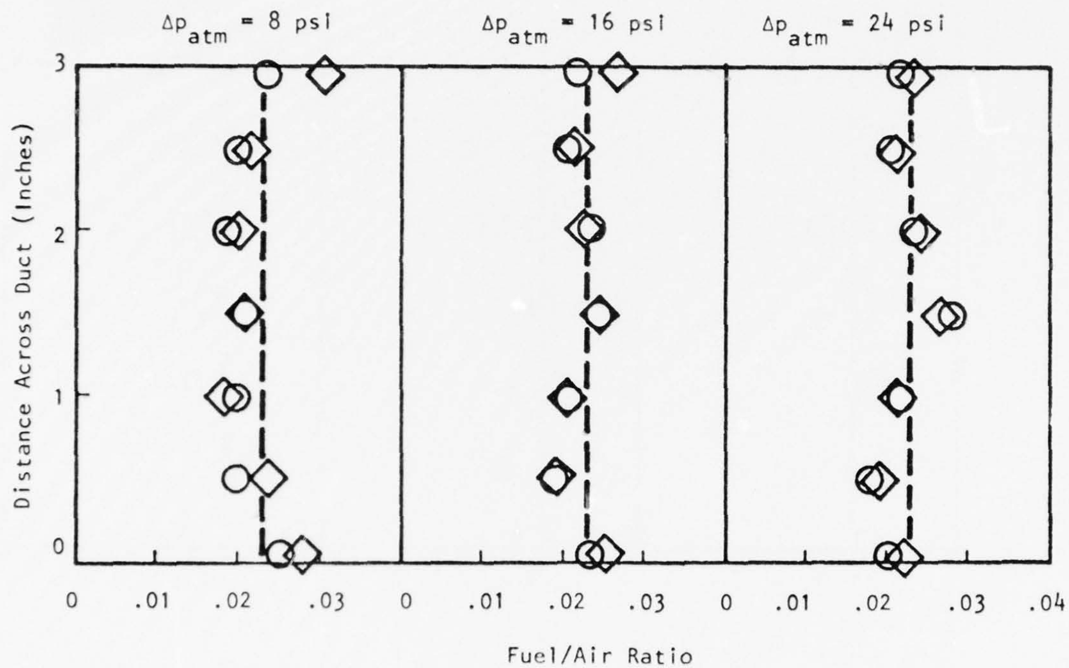


Figure 21d. Fuel Distribution Profiles at Station 13.5 (Condition 5)

Note: Circular and diamond symbols represent horizontal and vertical axes, respectively.

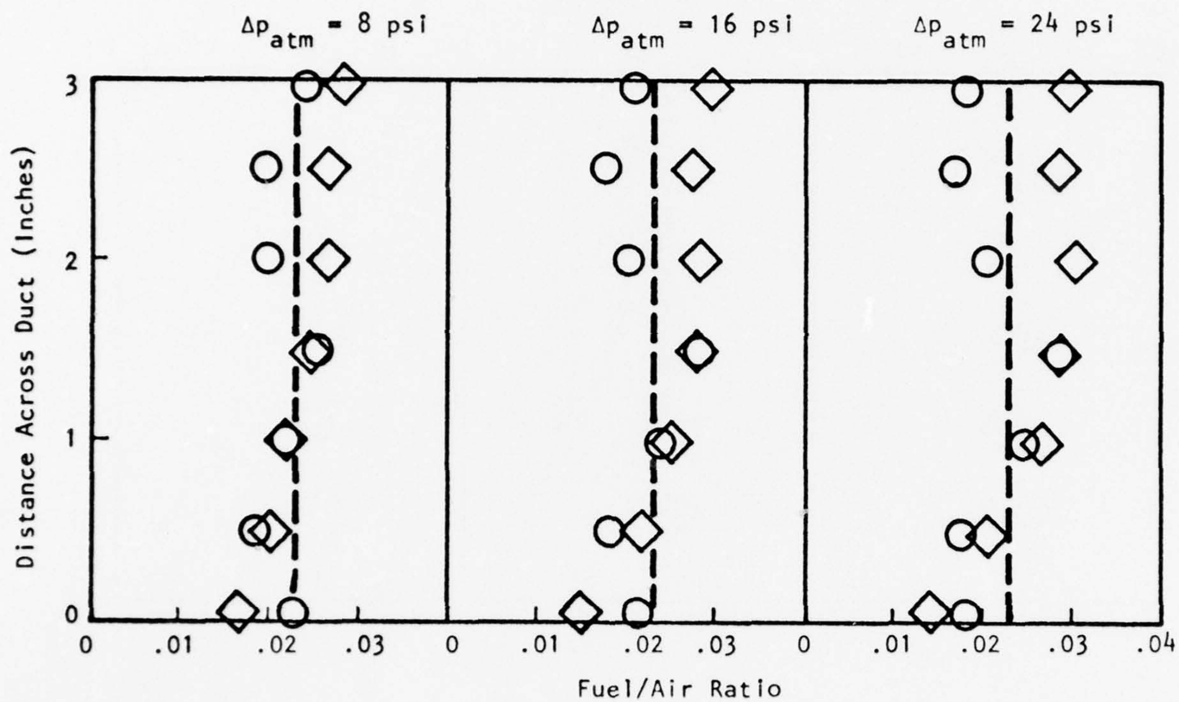


Figure 21e. Fuel Distribution Profiles at Station 13.5 (Condition 6)

Note: Circular and diamond symbols represent horizontal and vertical axes, respectively.

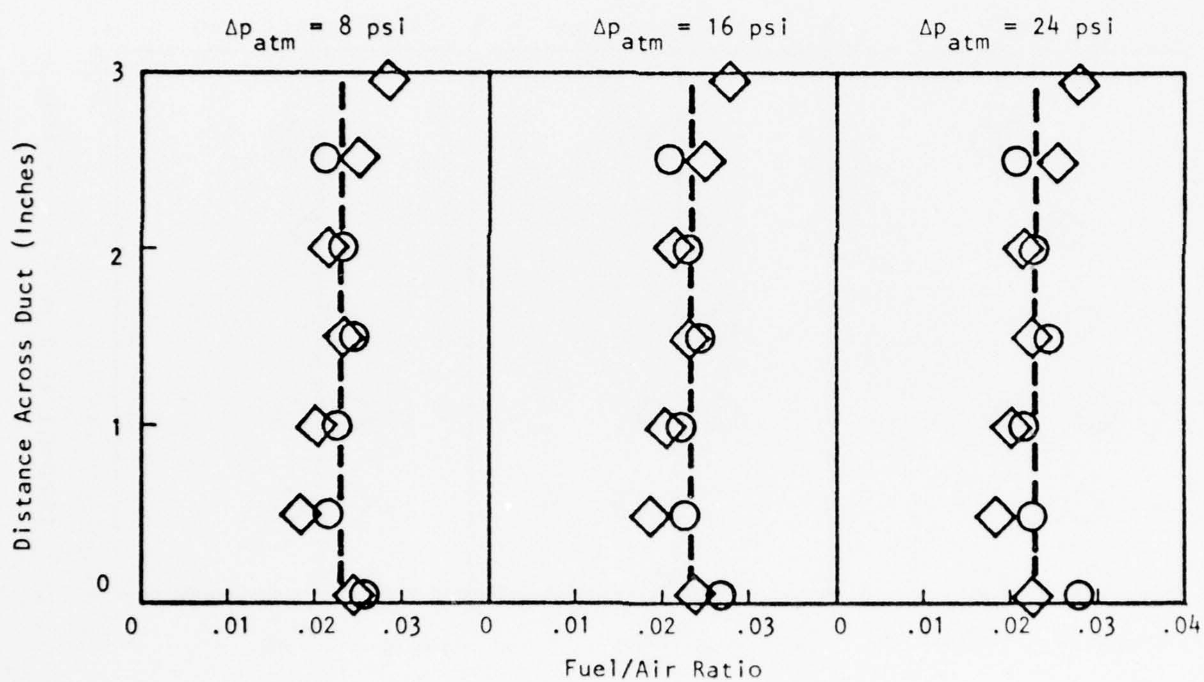


Figure 21f. Fuel Distribution Profiles at Station 13.5 (Condition 7)

NOTE: Circular and diamond symbols represent horizontal and vertical axes, respectively.

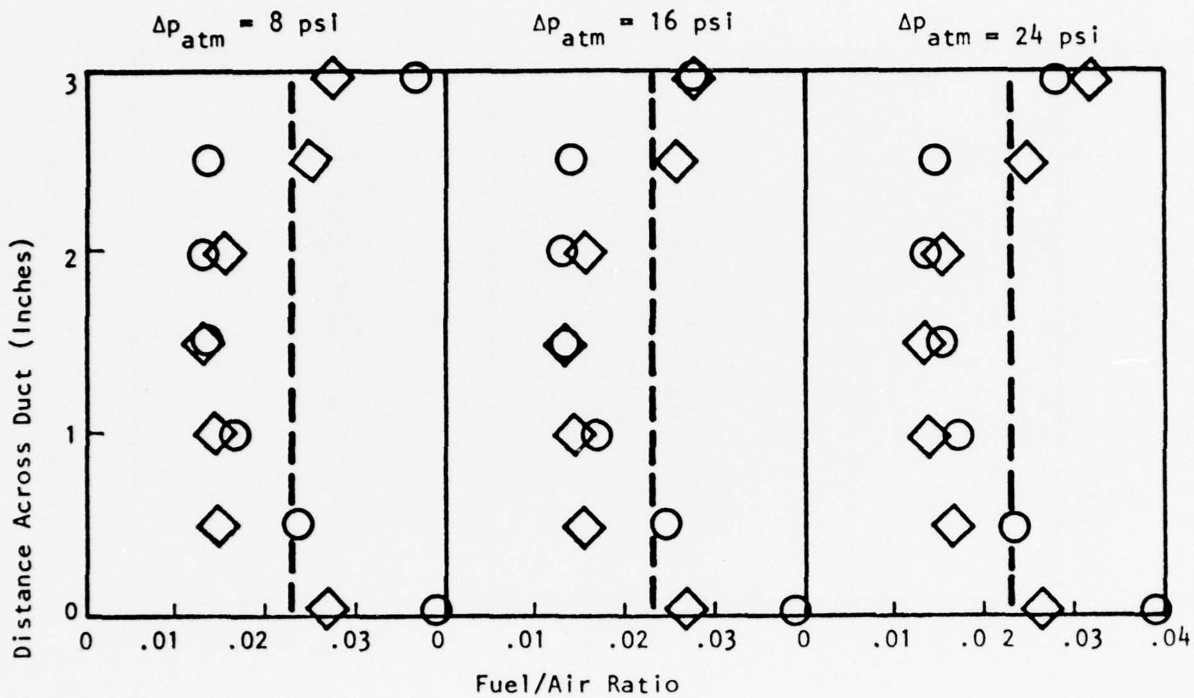


Figure 21g. Fuel Distribution Profiles at Station 13.5 (Condition 8)

Note: Circular and diamond symbols represent horizontal and vertical axes, respectively.

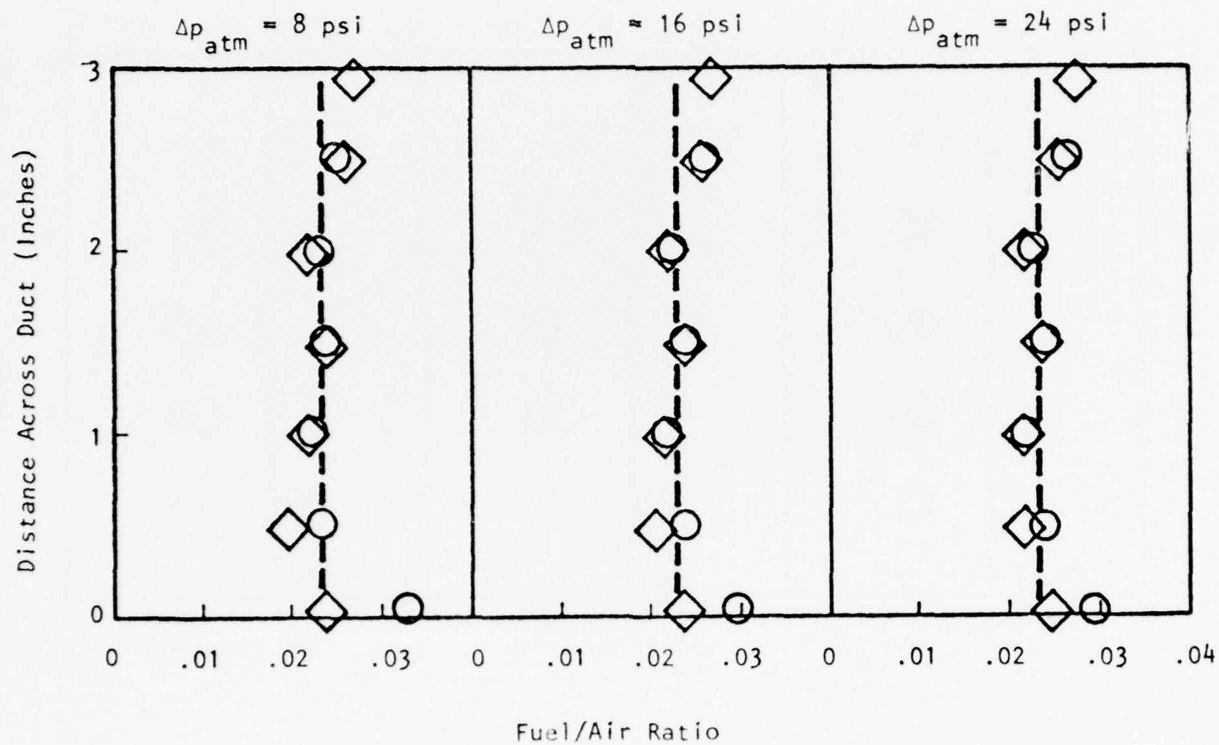


Figure 21h. Fuel Distribution Profiles at Station 13.5 (Condition 9)

At condition 5, where the inlet air temperature drops from 850°F to 700°F (see Table I), the low level of atomizing air results in a profile excessively biased toward the walls. In this case, increasing the atomizing air pressure differential to 24 psi eliminates the excessively high wall concentrations although a slight bulge in centerline concentration results. It was not possible to measure fuel profiles past the mixer centerline at condition 8 where the 250 psia pressure level caused the probe stem to act as a flameholder. As a result, it was only possible to acquire data for one atomizing air level at this condition and no conclusion can be drawn regarding its optimum value. The normalized RMS deviation of the exit plane fuel distribution from the ideal (completely uniform) is summarized in Table II. The average deviation (at the best atomizing air setting) over the range of conditions tested is 8.3%.

TABLE II

RMS DEVIATIONS (%) FROM IDEAL FUEL DISTRIBUTION AT EXIT

Condition	Δp = 8 psi	Δp = 16 psi	Δp = 24 psi
2	5.7*	10.3	11.8
3	5.3*	6.0	6.1
4	5.2*	6.0	7.9
5	24	11	8.2*
6	13*	16	20
7	13*	21	24
8		7-9*	
9	7.2*	7.8	11
10	10*	15	13

*Best condition.

SECTION VI
CONCLUSIONS

An evaluation of the operating characteristics of the pressure, air blast and air-assist fuel/air carburetion designs yields several very interesting conclusions. First, the initial dispersion of liquid droplets throughout the incoming airstream is a critical element determining the ability of a design to produce a uniform exit plane concentration in a device whose length is limited to a few duct diameters. In a non-swirling flow, a centrally mounted air-assist atomizer injecting in the streamwise direction produces an initial dispersion of liquid droplets heavily weighted toward the axis. The introduction of air swirl provides a mechanism to bias the initial droplet distribution toward the walls, improving it considerably. However, a single swirl angle was not found to be suitable across the entire duct. The optimum distribution of air swirl for a given design is evidently a function of the specific characteristics of the injector employed. However, for the air-assist atomizer employed here, a swirl angle of 40° in the central flow region and 25° near the walls yielded a reasonably flat fuel distribution profile.

The use of lateral jet penetration distance was found to be an inadequate design guide for the case of flush mounted wall orifice fuel injection. For the set of operating conditions encountered here, fuel jets injected through the walls were found to bend downstream, depositing most of the fuel near the axis of the mixer tube. The use of air swirl is an effective means of biasing the pressure injection fuel distribution toward the walls. However, an eight injection port design with a three inch diameter mixing tube did not produce circumferential symmetry within a distance of twelve inches making it unsuitable for use in the present application. Sidewall injection appears best suited to designs involving high fuel flow rates where the practical limits on orifice size are not restrictive.

The air blast design suffered from the major disadvantage of producing flow separation along the intersection of the wall and the injection blades. Since this separated flow region contained fuel, the relatively long residence times resulted in autoignition and flameholding.

In configurations where the fuel distribution was poor, autoignition was detected by the mixer exit thermocouples. The fuel (Jet A) residence time under these conditions was 15 msec, and is quite close to the 18 msec estimate based on JP-4 data. However, when mixing was improved, no autoignition was detected up to residence times of 25 msec. This is a property peculiar to a system such as that developed here where the combination of initial temperature and equivalence ratio is such as to produce an adiabatic flame temperature below the limits for stable combustion (typically around $2700^{\circ}F$). Thus, autoignition is avoided not by limiting the residence time but rather by limiting the time required to mix to a condition below the limit for maintaining combustion.

At temperatures as low as $700^{\circ}F$, atomized sprays of Jet A fuel were found to be completely vaporized within a distance of twelve inches from the injector (residence time 15 msec). The introduction of swirl made the performance of the system highly dependent upon air temperature by virtue of the link between droplet lifetime and total centrifugal impulse imparted. The system is far more sensitive to a drop in air temperature than it is to a temperature rise. In this design, the sensitivity to air temperature was counteracted by varying the intensity of the atomization field. In applications where this additional degree of freedom is not available, the application of swirl over a range of temperatures could lead to serious difficulties.

The use of substantial swirl was found to have a profound effect on the mixer velocity field. Clearly, no design can tolerate negative velocities at the exit plane. However, in premixing designs where the combustor entrance velocity profiles need not be highly uniform, high central swirl angles can be used to produce extremely flat fuel concentration profiles. In the present application, maintaining velocity uniformity was important in order to make the most effective use of a downstream catalytic reactor and swirl angle had to be limited to 40° to avoid an excessive centerline velocity decrement. In all cases, the low velocities associated with this system produced a total pressure drop of less than 1%.

The air-assist atomizing nozzle employed here was not sensitive to changes of ± 22% in fuel flow rate. Increasing system pressure did not produce any basic difference in fuel distribution, however, the profiles did tend to become somewhat asymmetric. This would appear to be an effect associated with the ability of the Sonicore atomizer to maintain a symmetric auxiliary air flow at high injection rates. Nevertheless, there appear to be no fundamental problems associated with higher pressure operation. Finally, air velocity changes of ± 25% have little effect on operation of the unit.

APPENDIX

DESCRIPTION OF INSTRUMENTATION

The program of experiments described in this report requires the measurements of velocity, fuel distribution and degree of vaporization across given planes within the carburetion unit. These measurements were made using the phase discrimination sampling probe illustrated in Figure (A-1). The probe is provided with a pitot tube, a stagnating thermocouple and an air cooled sampling tip. The probe is mounted in a 4-inch extension spool provided with wall static pressure taps at two locations along a line normal to the probe stem.

Temperature surveys are made using the stagnation thermocouple (temperature levels here are low enough to allow the use of an unshielded thermocouple). Velocity profiles are obtained by measuring the pressure difference between the pitot and wall static pressure taps. It should be noted that velocity should, in principle, be derived from a static pressure measurement on the probe. However, in this case, the low subsonic Mach numbers and absence of substantial streamline curvature reduce the error involved with the use of wall taps to an acceptable level.

The probe was originally designed to measure velocities in an axially aligned system. The subsequent introduction of substantial swirl made the use of such a probe invalid since the specification of velocity required measuring the orientation as well as the magnitude of the air speed vector. Under conditions of flow misalignment, substantial errors could be introduced at the probe tip and the assumption of constant static pressure across the section of a swirling flow is incorrect.

In order to overcome these difficulties, a honeycomb air straightener (1/8-inch cell by 3/16-inch depth) was installed 1.5-inches upstream of the probe for the measurement of velocity. The use of this air straightener allowed an accurate determination of velocity at the probe station. However, this is not the velocity which would exist immediately upstream of a catalytic reactor since this flow would still be swirling. Rather, it represents the

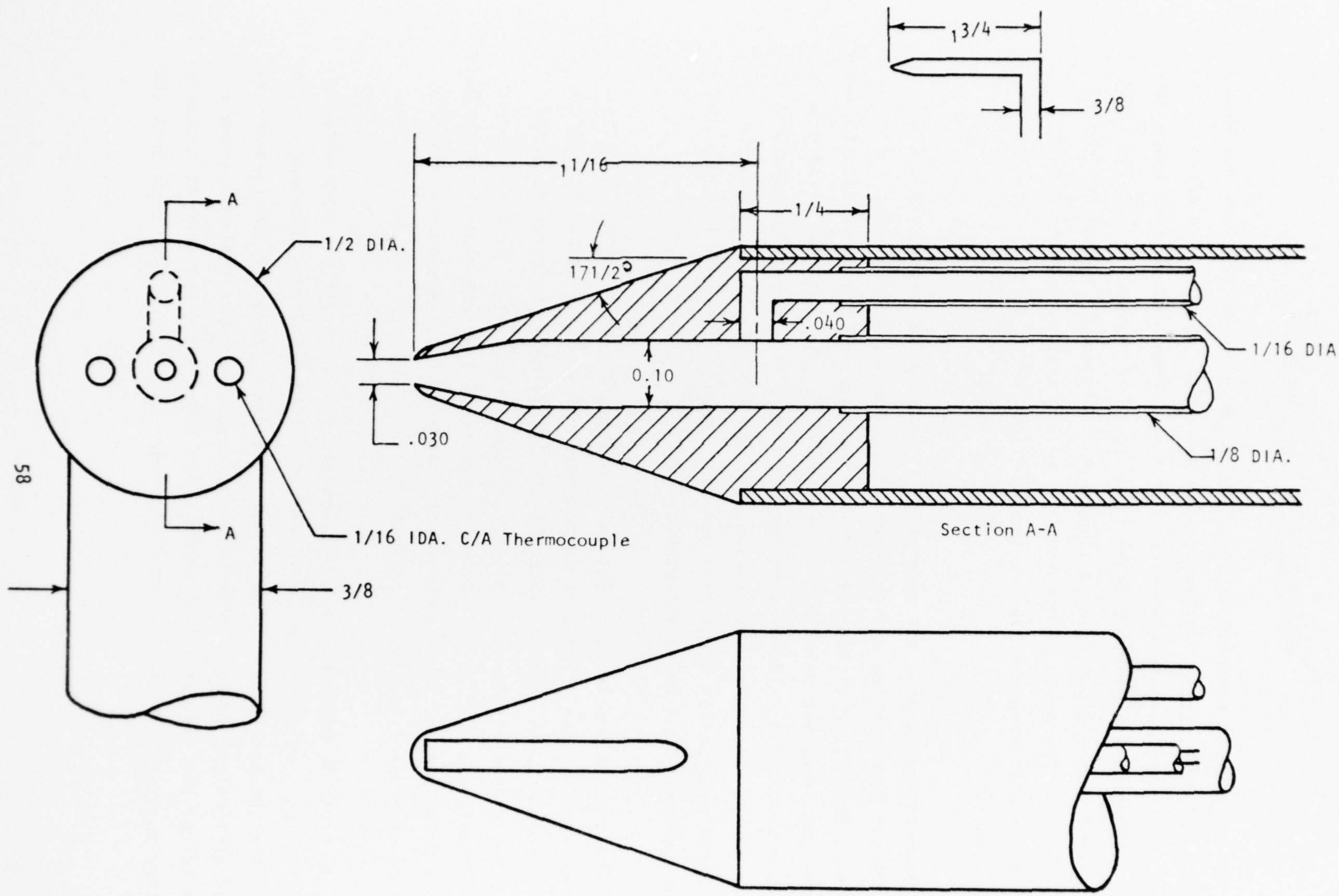


Figure A1. Phase Discrimination Probe

velocity entering a multicelled reactor unit and, as such, is a measure of the loading uniformity of such a unit. Since this is exactly the characteristic of interest, the use of this technique is justified in the present case.

The sampling probe is provided with a slightly expanded internal duct with a lateral bleed hole drilled through the wall at right angles to the flow. The velocity, temperature and pressure measurements determine the local mass flux and permit the total sampling rate to be throttled downstream to produce an isokinetic condition at the probe entrance. In a stream containing both liquid and gaseous fuel, the captured sample indicates the total local fuel concentration. By withdrawing a small amount (typically 10%) of the sample through the lateral bleed hole, liquid droplets are excluded by virtue of their inability to negotiate the right angle turn and a sample is obtained which indicates the gas phase fuel concentration. A comparison of fuel/air ratios obtained from the primary and lateral bleed samples yields the relative fractions of liquid and gas phase fuel and thus the degree of vaporization.

There is implicit in this method the assumption that droplets with diameters of less than 1-2 microns which are capable of negotiating the sharp turn into the lateral bleed hole are to be considered as gas phase. This is an unfortunate but necessary assumption associated with the use of any centrifugal separation scheme. However, since droplets of this size represent an extremely small mass fraction and evaporate quite rapidly upon entrance to a reaction zone, the assumption does not introduce a serious error.

The GASL gas sampling system is illustrated schematically in Figure (A-2). The sampling port is connected by a 30-foot length of 1/4-inch stainless steel line to a high flow pressure regulator and dump valve. The sample pressure is regulated down to 2 atm before the gas is divided by a set of metering valves into four individual streams. The sample line is heated to a temperature of 350°F up to a Beckman Model 402 hydrocarbon analyzer which accepts one of these streams: the remaining three sample streams are allowed to cool to 195°F. The sample line is heated by wrapping it with an asbestos cloth resistance heater and enclosing the assembly with a fiberglass/plastic foam insulating sheath. One of the sample streams is passed through a Beckman Model 951 NO/NO_x

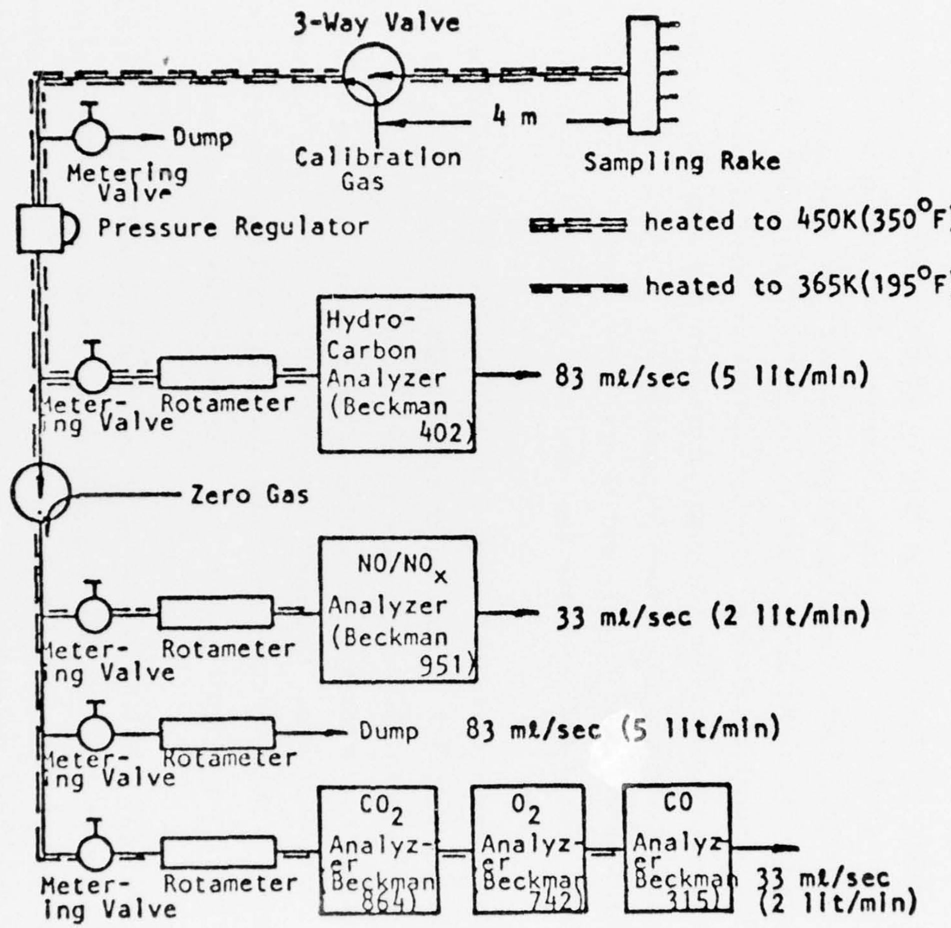


Figure A-2. Gas Sample Analysis System

analyzer (chemiluminescence). Another leads to a Beckman Model 864 infrared analyzer (CO_2), a Beckman Model 742 oxygen analyzer (Polarographic) and a Beckman Model 315B infrared analyzer (CO), connected in series. The last line is used as a dump. Flow rates through the system are kept high by maximizing the amount of sample dumped both up and downstream of the pressure reduction regulator. Calibration gas is introduced through a three way valve located just downstream of the sample manifold. Zero gas for the oxygen, CO_2 and CO analyzers (dry nitrogen) enters through a three way valve located upstream of the set of metering valves. The NO/NO_x and hydrocarbon analyzers provide internal sources of zero gas. Gas analysis procedures and data reduction practice is conducted in accordance with SAE ARP 1256.

The sample analysis system described here is intended primarily for the processing of combustion products rather than the combustion reactants which are collected in the present case. The principal difference, of course, is the level of unburned hydrocarbons in the sample stream. The hydrocarbon analyzer is intended for the analysis of trace species and its use with samples containing more than 1% hydrocarbon species results in a highly nonlinear output characteristic and occasional saturation of the instrument. Since even a perfectly mixed carburetor exhaust sample can contain up to 3% fuel, and higher local concentrations are occasionally encountered, the use of the standard gas analysis system is not appropriate here.

This difficulty is overcome by the addition of a small catalytic reactor. The reactor consists of an insulated pressure tube filled with an appropriate catalyst.* The catalyst bed is preheated to a temperature of $700^{\circ}F$ by an embedded electric resistance element. The fuel-bearing gas sample withdrawn from the carburetor enters the reactor where its combustion is catalyzed. The degree of combustion efficiency is not extremely important as long as most of

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*In this case, the catalytic element employed was 1/8" pellets of 0.3% platinum on gamma alumina (Girdler T309D).

the hydrocarbon captured is converted into CO and CO_2.* The reactor exhaust gas is then passed through a heat exchanger and into the gas sampling system where an accurate analysis is made to yield fuel/air ratio through the carbon balance. Catalytic reactors were installed on both the primary and the lateral bleed sample lines.

Carburetor entrance conditions were characterized with the use of a point cruciform rake equipped with radiation-shielded chromel-alumel thermocouples and pitot tubes. The carburetion unit was equipped with surface instrumentation only: static pressure taps and wall thermocouples. Fuel flow rates were measured using a Fisher-Porter turbine flowmeter. Two thermocouples were mounted 180° apart at a station 11 inches downstream of the injection station. The thermocouples were installed flush with the interior mixer wall and were used to detect autoignition/flashback.

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*In operation, the catalytic reactors converted virtually all captured fuel to CO_2 with CO and unburned hydrocarbon readings generally less than 10 ppm.

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